Developing a Radio Frequency Enclosure for the Multiplicity Vertex Detector of the PHENIX Experiment

by

Richard Conway

Submitted to the Department of Mechanical Engineering
in partial fulfillment of the requirements for the degrees of

Bachelor of Science

and

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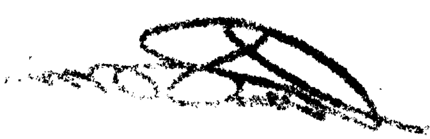

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Abstract

The Radio Frequency Enclosure is an environmental shield for the Multiplicity Vertex Detector, which is a central subatomic particle detector in the PHENIX physics experiment being performed at the Relativistic Heavy Ion Collider at the Brookhaven National Laboratory. The RF enclosure is designed to provide mechanical protection of the MVD and isolate it from external RF noise, temperature, and humidity while adding as little mass to the detector as possible.

The RF shielding is made of a thin aluminum foil, and Mylar film is used to keep out the external air. Rohacell foam, a high strength and low density polymethacrylimide foam, is used as the structural support for the enclosure, which helps to minimize the added mass.

The RF enclosure design was developed to the production stage. During the development process, the details of the fabrication, assembly, and installation procedures were finalized and then documented. Additionally, all the tools and fixtures needed for fabrication, assembly, and installation were designed, built, and tested. A prototype enclosure was tested for RF attenuation and air leakage, and the results of both tests indicate that it will adequately shield the MVD's internal components.

Thesis Supervisor: Woodie C. Flowers
Title: Pappalardo Professor of Mechanical Engineering

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Section 1: Introduction

1.1 Overview of work

This paper summarizes the work that I have performed in researching, designing, fabricating, assembling, installing, and testing the Radio Frequency (RF) Enclosure of the Multiplicity Vertex Detector (MVD). Testing has shown that the design can be fabricated, assembled, and installed so that tolerances on all specifications can be met and that the RF enclosure can adequately perform the tasks required of it.

The RF enclosure is a component of the MVD. The MVD is a subatomic particle detector in the PHENIX Experiment, which will be operated at the Brookhaven National Laboratory's Relativistic Heavy Ion Collider (RHIC).

1.2 Overview of RHIC

The Relativistic Heavy Ion Collider (RHIC) is a particle accelerator being built at the Brookhaven National Laboratory (see Figure 1-1).

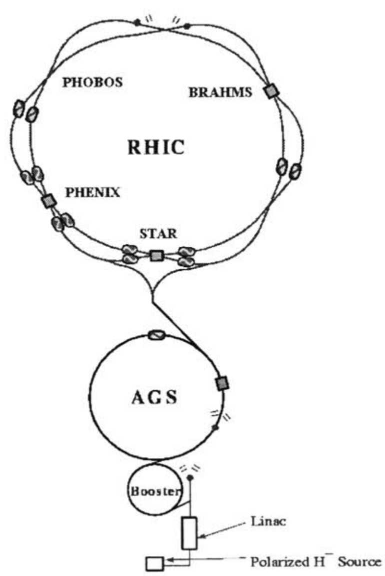

Figure 1-1: The Layout of RHIC at BNL

It will have the capability of colliding heavy ions at energies of 100GeV in each beam.[1] Quantum Chromodynamics (QCD) predicts that heavy nuclei collided at these ultra-relativistic energies will undergo a phase transition from ordinary hadronic matter to a quark-gluon plasma (QGP).[2] QGP is the as-of-yet unseen form of matter believed to have existed immediately after the Big Bang.

Four major experiments: PHENIX, STAR, PHOBOS, and BRAHMS, are under construction at RHIC in order to study QGP physics as well as the physics of polarized proton collisions.[1] RHIC is scheduled to become operational in the Summer of 1999. The first RHIC heavy ion physics run will commence in the Fall of 1999.[3]

1.3 Overview of PHENIX

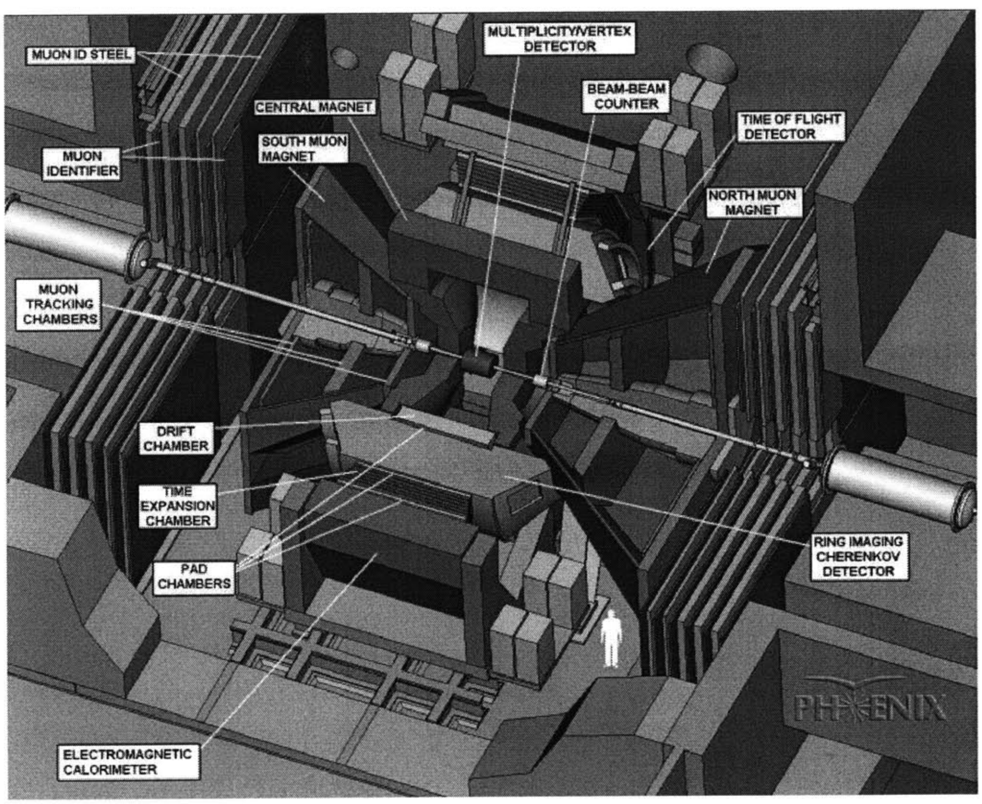

Figure 1-2: The PHENIX experiment's detector layout

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1. Obtained from http://www.phenix.bnl.gov/export1/docs/html/RHIC.html
2. Obtained from http://www.phenix.bnl.gov/phenix/WWW/html/physics.html
3. Obtained from http://www.phenix.bnl.gov/phenix/WWW/home/phenix_5w.html

PHENIX is a very large particle detection experiment, which is designed to detect, identify, and measure the characteristics of each of the many different kinds of particles (electrons, muons, hadrons, and photons) produced at RHIC. PHENIX is comprised of four magnets, four instrumented spectrometers or arms (two electromagnetic and two muon arms) and two inner detector subsystems (see Figure 1-2). The PHENIX Collaboration consists of over 430 physicists and engineers from 43 participating institutions in 11 countries (Brazil, Canada, China, Germany, India, Israel, Japan, Korea, Russia, Sweden, and the USA). A comparable number of support personnel also work on PHENIX.[3]

Among the major goals of PHENIX are: 1) investigating the Quantum Chromodynamics prediction of a deconfined high-energy-density phase of matter, 2) searching for the quark gluon plasma, and 3) exploring the physics of this new state of matter. PHENIX will also study the physics of polarized proton collisions in order to uncover the secrets of the spin structure of the proton. Currently it is known that the three quarks do not carry all of the spin of the proton. The rest of the spin might be carried by the gluons, sea quarks, some combination of these or by some as yet undiscovered mechanism.[2]

1.4 Overview of the MVD

The Multiplicity Vertex Detector (MVD) is the innermost detector of the PHENIX experiment. The MVD's main physics goals are: 1) to provide a multiplicity measurement ($dN/d\eta$) to the PHENIX Level-1 trigger, 2) to measure fluctuations within the multiplicity distribution on an event-by-event basis (which potentially can be associated with the formation of Quark Gluon Plasma), and 3) to determine the collision vertex. The detector has full azimuthal coverage with good granularity and is capable of reconstructing the collision vertex to approximately 100μm in each of three dimensions.

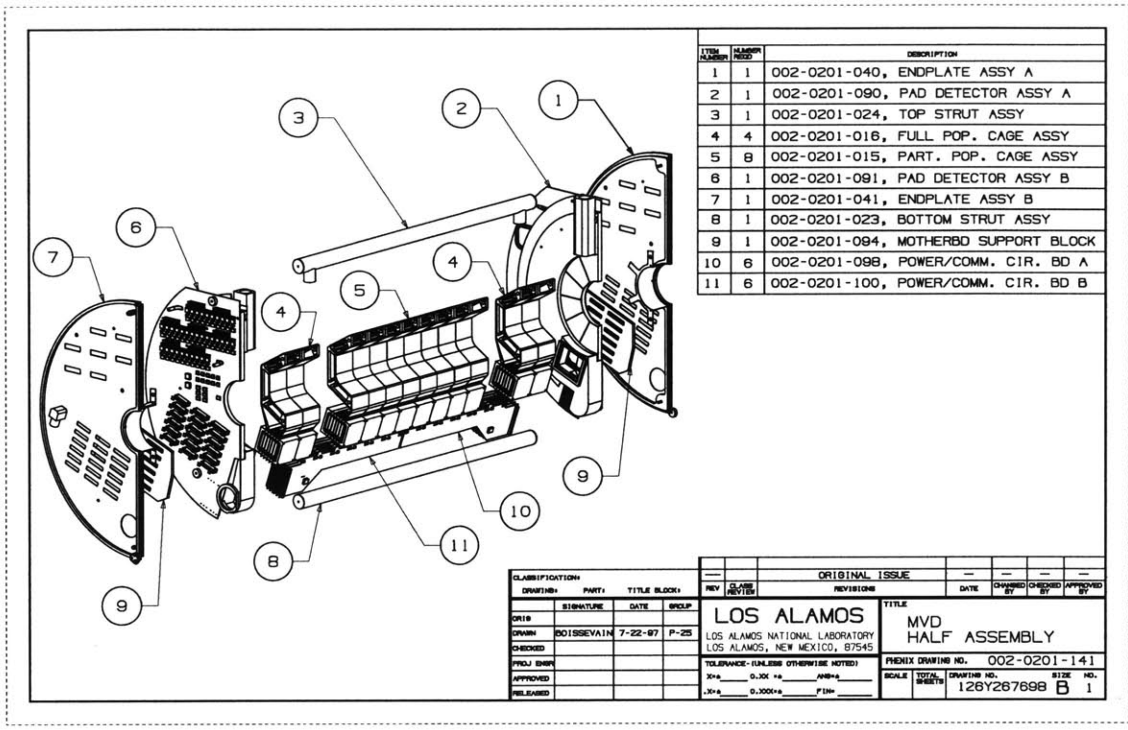

Figure 1-3: Exploded assembly drawing of one half of the MVD

The MVD is a clam-shell design, constructed in two halves to close about the beam pipe (see Figure 1-3). The 64cm long central barrel of the detector is comprised of two concentric layers of silicon strip detectors located at 5cm and 7.5cm from the beam. There are 112 strip detectors with 256 strips on each detector at 200mm strip-pitch. On each end of the central barrel there is a silicon disk comprised of twelve wedge-shaped pad detectors. Each pad detector has 252 elements that increase in size from 2mm x 2mm at the inner radius to 4.5mm x 4.5mm at the outer radius.[4]

Each silicon strip and pad is read-out independently. This requires that there be a tremendous amount of signal processing performed inside the MVD. The detector front-end electronics must have the ability to continually process data at an estimated maximum rate of one collision event every 100ns. These front-end electronics are encapsulated in several custom CMOS chips which

4. PHENIX-MVD-97-29, PHENIX Note 313

house a preamplifier, discriminator, analog memory unit, and analog to digital converter. The system has pipelined acquisition, performs in simultaneous read/write mode, and is clocked by the 10 MHz beam crossing rate at RHIC. These die, together with a pair of commercial FPGA's that are used for control logic, are packaged in a multi-chip module (MCM).[4]

The total allowed mass budget of the MVD is very restrictive. This is especially true in the central barrel region of the detector which shadows the acceptance of the PHENIX electron arms. In order to minimize the mass in the MVD, low density Rohacell IG-71 foam has been used as the support structure wherever possible. The total average radiation length in the central barrel is approximately 1%; the combined mass of the support structure, RF enclosure, and kapton cables connecting the silicon strips to the MCMs contribute approximately 0.4% of a radiation length, and the two layers of silicon strips add 0.6%.[4] This allows for 99% of the radiated particles to be absorbed by surrounding detectors while still allowing the MVD to accomplish the tasks of determining the charged particle multiplicity and collision vertex.

1.5 Overview of the RF Enclosure

The Radio Frequency Enclosure (see Figure 1-4) is an environmental, mechanical, and electronic shield that isolates the MVD from the outside environment. The main environmental hazards to the MVD's effectiveness are: 1) external RF noise, 2) humidity, 3) high temperatures, and 4) physical damage to the silicon or front-end electronics.

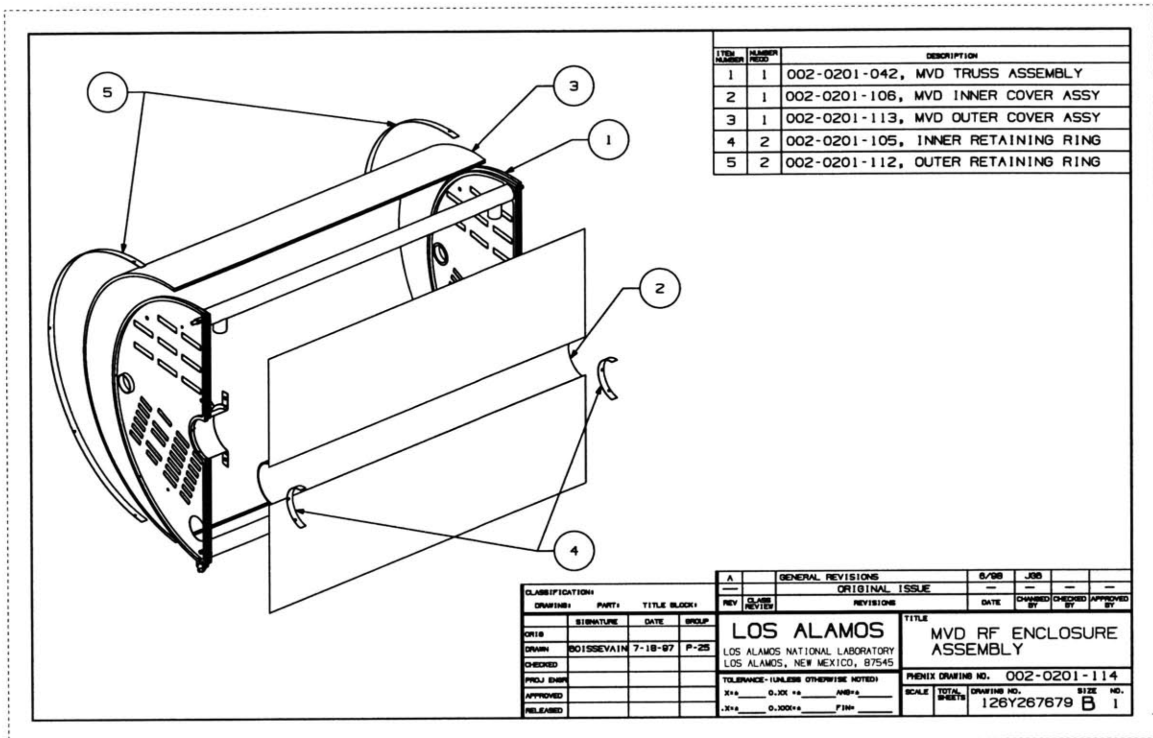

Figure 1-4: Exploded view of the MVD's RF Enclosure

The MVD must be isolated from external RF noise to ensure that the noise radiation is not absorbed by the silicon detectors or readout electronics, which could lead to inaccurate collision vertex and multiplicity findings by the software algorithms. If the silicon support structure (Rohacell foam) absorbs humidity, then it expands, which can cause the central silicon barrel to move and thereby hamper the accuracy of the vertex finding algorithms and perhaps even damage the silicon strip detectors. High temperatures should be avoided in order to keep the silicon detectors running at their optimum efficiency levels as well as to keep the front-end electronics and motherboard electronics from overheating.

In addition to isolation from these environmental hazards, it must also fit into the geometric allowance for the detector, absorb as little of the QGP radiation as possible, be either reusable or replacable, and have minimal cost. In order to meet these functional requirements, the base design parameters for the RF enclosure are that it: 1) use hemi-cylindrical sheets of Rohacell foam to give it thermal isolation, strength, and shape while minimizing particle absorption, 2) use Mylar film to provide an air-tight and water-tight seal, and 3) use thin aluminum to provide RF shielding.

Section 2: General notes on RF noise and shielding

2.1 What is RF noise?

Radio frequency noise is electromagnetic interference in the range of radio frequencies. It can be conducted and/or radiated. It is generated by all electrical systems that operate in that range of frequencies, but the particular sources expected to be relevant to the MVD are the electronics associated with the other particle detectors in the PHENIX experimental hall and the particles colliding in the beam pipe. If the amplitude of the RF noise reaching the MVD's sensitive electronics is high, then it can have a significant impact on the ability of the MVD's software to discern the correct multiplicity and vertex of particle collisions.

According to Webster, radio frequencies are electromagnetic wave frequencies intermediate between audible frequencies and infrared frequencies,[5] which have wavelengths roughly between 1000m and 10m; however, in this document radio frequency noise is considered to be any electromagnetic noise that can affect the MVD. This is because a large majority of the electromagnetic noise expected to be encountered in the PHENIX experimental hall is RF noise, but due to the impulse-like noise generated by the wave crossings in the beam pipe, there will be some noise that reaches into much higher frequencies.

2.2 The need for shielding

The two ways of avoiding RF noise are to reduce the noise generated and/or to reduce the noise received. Because the amount of noise generated is uncontrollable in the MVD's particular situation, the focus will be on reducing the amount received. There are three ways to do that: shield the source, shield the receiver, and increase the distance between the source and the receiver. The other particle detectors are responsible for shielding themselves as much as reasonably possible, and because the amount and type of shielding they will

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5. *Webster's Seventh New Collegiate Dictionary*, 1967. G&C Merriam Co., Springfield, MA.

provide is currently unknown, it is assumed that they will not provide enough shielding for the MVD to neglect the noise they transmit. Additionally, the distances between the sources and the receiver are fixed, because the detector layout in the PHENIX experimental hall has been fixed. Therefore, the MVD must shield its receivers to perform optimally.

2.3 RF shielding

A shield is a partition between two regions of space such that the electric and magnetic fields of interest are attenuated in passing from one of these regions to the other[6]. Every electromagnetic wave striking a metallic surface is reflected, transmitted, and absorbed in certain proportions. The shielding efficiency (SE) is the total attenuation measured in decibels of the shield and is the sum of the reflection loss (R), absorption loss (A), and correction term for multiple reflections loss (C): $SE = A + R + C$. For most metallic surfaces, the reflection loss to plane waves is so large that only a small fraction of the energy that strikes the surface will enter the metal.[6]

The reason for a shield's effectiveness can be explained in terms of the skin effect. For shield thicknesses that reduce any currents induced on one side to zero on the other side, there can be no electromagnetic field on the side with zero current. The current decreases exponentially through the shield thickness as can be seen in Equation 2-1, so it actually will never reach zero no matter how thick the shield is. In Equation 2-1, F is the field intensity at a distance S inches away from the surface, F_o is the same field intensity at the surface, ρ is the resistivity of the material in Ω-circular-mils per foot, μ is the relative permeability, and f is the frequency in Hertz.

$$F = F_o e^{-1.238\sqrt{\frac{\mu f S^2}{\rho}}} \qquad \text{(Eq. 2-1)}$$

Because of this exponential decrease, a perfect shield is theoretically impossible to make. However, at high frequencies, attenuation is rapid and the shield can be

6. *Handbook on Radio Frequency Interference*, 1962. Frederick Research Corporation.

thin and still reduce the transmitted noise to practically undetectable levels.[6]

There are three idealized mathematical models that can be used to estimate the shielding efficiency of a shield. Each model uses a different approximation of the noise's wave impedance to arrive at its closed-form solution. The far-field model approximates the noise as plane waves. It is only valid when the noise sources are more than several wavelengths away from the receiver, and it leads to a fixed wave impedance (Z_W) that is the ratio of the electric field intensity to the magnetic field intensity. The electric (or magnetic) field model approximates the noise as a pure electrical (or magnetic) field which assumes that the field is created by a high voltage and low current (or low voltage and high current). It is only valid when the electric (or magnetic) field intensity is "much larger" than the magnetic (or electric) field intensity.

The reflection and absorption losses are functions of the shield material, whether the noise is electric or magnetic, the impedance of the source, the frequency, and to some extent the surface texture[7]. Because of these dependences their values differ depending on the field model used. Values for 1mil thick aluminum shielding 1m from the source are plotted using the three different models in Figure 2-1. The original data and derivation of the results can be found in Appendix 1. The equations used to calculate the values for each model were taken from Appendix 6 of the *Electrical Interference Handbook*[1].

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7. Ellis, N., 1998. *Electrical Interference Handbook, 2nd Ed.* Reed Educational and Professional Publishing Ltd., Woburn, MA.

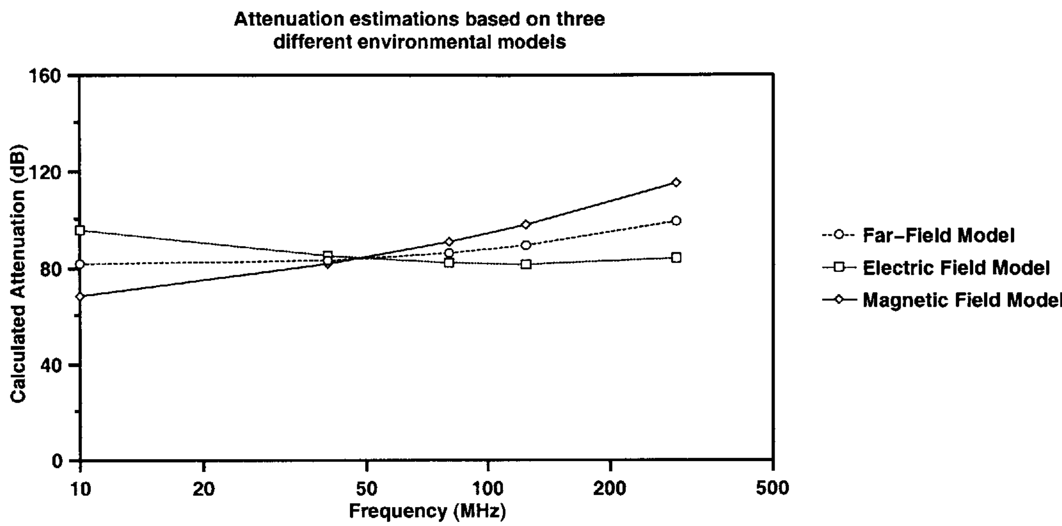

Figure 2-1: RF shield attenuation estimations using different source models

The diamonds represent the magnetic field model, the squares represent the electric field model, and the circles represent the far-field model. As can be seen, the electrical field and magnetic field models bound the extremes of the expected attenuation and show opposite dependence on frequency. The far-field model is approximately the mean of the other models. This is because it assumes that there is both an electric and magnetic field.

As mentioned these calculations are only valid in ideal situations. Any holes, joints, or irregularities decrease the shielding efficiency depending on their dimensions relative to the noise wavelength, but the calculations can be used to provide a rough approximation. When openings are necessary (e.g. for air cooling purposes) they must be specially designed to minimize their interruption of the induced current flow and strongly attenuate any radiation through them.[6]

The RF noise environment in the PHENIX experimental hall will have a mix of electrical, magnetic, and far field sources, but their relative proportions have not been determined and the design of the MVD's shield has been completed. The shield was designed so as to attenuate as much RF noise as possible without violating the constraints of size and radiation length.

Section 3: Isolating the MVD from the outside environment

3.1 Isolation from RF noise

If the RF noise inside the MVD is too high, then the MVD electronics will not be able to determine if the radiation absorbed by the silicon is from the heavy ion collision or from the RF noise. And if it can't determine which radiation is from the collision, then it cannot determine the multiplicity or vertex.

In order to keep the system signal-to-noise ratio for a single Minimum Ionizing Particle (MIP) signal at greater than the specified 10:1 ratio, it has been determined that the noise inside the MVD must be less than 2500 electrons rms. But how difficult it will be to meet that specification remains to be seen, because the RF noise inside the PHENIX Experimental Hall, where all the PHENIX detectors are located, is unknown and will not be known until all the detectors are in place and running. Therefore, the MVD should be prepared for the worst case scenario, i.e. RF noise at a large range of frequencies at high amplitudes.

To shield against high frequencies (and short wavelengths) the shielding cannot have large holes as are in a Faraday cage, because the larger the holes the bigger the wavelengths that can seep through them. When extrapolated to the extremely high RF frequencies found in the near square waves that will probably exist in the PHENIX Hall, the shield must be completely solid (no holes) in order to keep out the RF noise. To shield against high amplitudes in lower frequencies, a thicker shield must be used to provide adequate shielding. However, a thick, solid shield adds significantly more mass to the detector than a wire mesh shield, and adding more weight means absorbing more of the QGP radiation.

Two functional requirements conflict with each other: minimizing the absorption of QGP radiation and blocking out external RF noise; therefore, a balance was struck between the shielding provided and the mass added to the detector.

For plane waves, the amount of RF shielding provided per unit thickness decreases exponentially as the thickness of the shielding material is increased[6]. So the optimal thickness of shielding corresponds to the point at which the exponentially decreasing “thickness versus shielding” curve intersects the undetermined “thickness versus QGP radiation absorption” curve. The problem is that the “thickness versus shielding” curve cannot be determined until the RF environment in the PHENIX experimental hall has been determined, and that will not be determined until all the detectors are installed and running.

Even if the environment could be determined it is not an issue in any case, because the RF shield design specifies that the shielding must attenuate the noise to the 10:1 signal-to-noise ratio. So the design thickness does not necessarily correspond to the optimal thickness for the shielding concerns, but instead it is determined by the needs of the MVD’s silicon, electronics, and software. However, this does not help either, because the thickness needed to meet the 10:1 ratio cannot be determined without a known RF environment.

Because estimating the frequencies and amplitudes of the RF noise to within any useful range is not possible, the RF shield design has been specified with the hope that it will provide adequate attenuation. The design that was chosen is a two-layered aluminum foil shield that completely encloses the MVD. The 0.5mil thick foil layers are separated in the surfaces concentric with the silicon barrel, but make electrical contact at the endcap surfaces and run to ground through a common wire.

3.2 Isolation from air leaks

The MVD needs to be isolated from the outside environment so that the inside temperature and humidity can be controlled. If the temperature rises above 50 Cthen the CMOS chips in the front-end electronics will be damaged, and if the radiation from the heavy ion collisions chronically damages the silicon, then cooling them down will help to decrease the effects of the damage. If the relative humidity inside the MVD differs between the environment where it is installed and the environment where it operates, then the hygroscopic Rohacell, which holds the silicon in place, will change shape and decrease the accuracy of the vertex finding algorithms.

Dupont's Mylar film has been chosen to keep the inner surface of the MVD air-tight. Mylar is a polyester film that provides a barrier to gas and water vapor as well as excellent flex and puncture resistance.[8] Each of two 0.5mil thick Mylar sheets is adhered to a 0.5mil thick aluminum foil shield and fit snugly into one of two concentric O-ring grooves to seal the inner surface (see Figure 6-1).

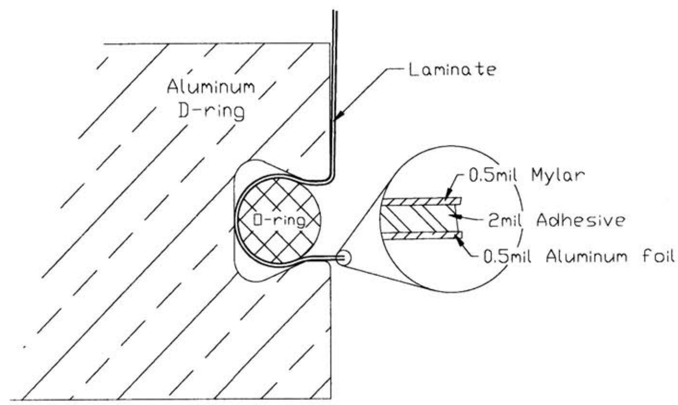

Figure 3-1: Detail of O-ring groove and enclosure laminate

The outer surface is kept air-tight by a 0.25" thick Rohacell cover sandwiched between two layers of 0.5mil thick aluminum foil and held in place by a 1/32" thick aluminum retaining ring (see Figure 6-2).

8. Obtained from http://www.dupont.com/packaging/products/films/index.html#mylar

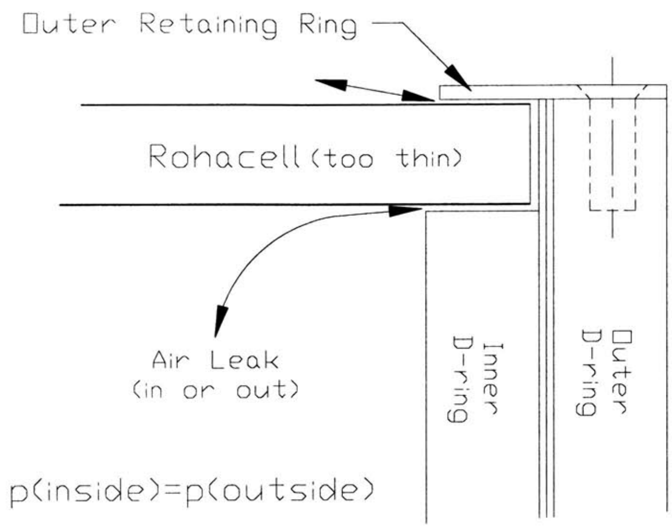

Figure 3-2: Outer enclosure air leak possible flow path

Each endcap is kept air-tight by two 1/64" thick aluminum endplates positioned between two aluminum D-rings (see Figure 6-3).

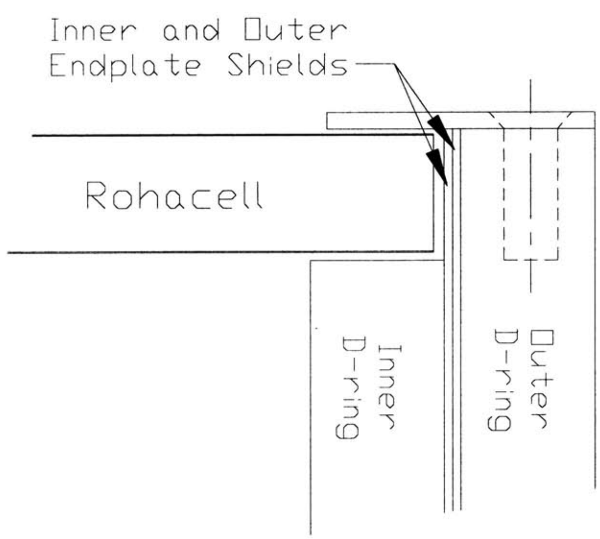

Figure 3-3: Cross-section detail of D-rings and endplates

There are a few spots on the inner surface that make a completely air-tight and RF-tight seal difficult to accomplish. The corners where the O-ring grooves of the D-rings and the seal strips meet are not filleted, and so cause a large amount of strain in the Mylar/ aluminum foil laminate. If the strain exceeds the laminate's maximum allowable strain, then the laminate will tear and result in an air leak and possibly an RF leak as well. In order to lessen the strain and ensure that no such tears occur, a small amount of tacky putty is placed in the O-ring grooves at the corners. This putty has been found to retain its properties after many weeks of being exposed to the environment it remains in while inside the RF enclosure. Even if one of the laminates tears, the other laminate in the assembled enclosure will be able to attenuate some of the RF noise and provide the for air seal.

Two other spots that are difficult to seal are the points where the inner Rohacell cover and the inner retaining ring meet the O-ring grooves. These sections are shown in Figure 6-4.

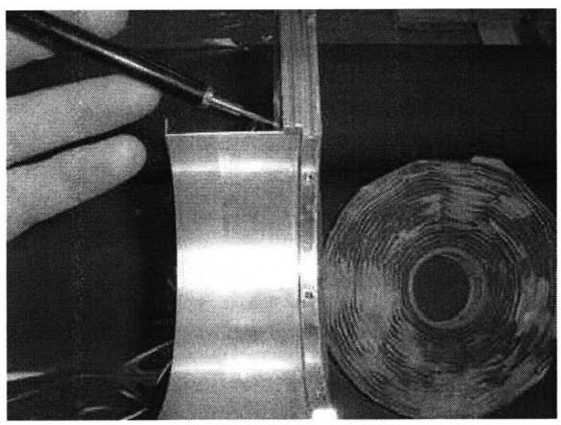

Figure 3-4: Difficult seal points

Again there is a large amount of strain imposed on the laminate at the points where the retaining ring and Rohacell meet the O-ring grooves, and again tears are avoided by putting a small amount of tacky putty in the O-ring groove at that junction in order to ease the strain of the laminates. Cutting the O-rings short of reaching the end of the groove has also been shown to ease the strain.

3.3 Isolation from temperature gradients

The environment inside the MVD is controlled by the air and water cooling systems, but should the systems fail, the RF enclosure covers will lower the heat transfer rate between the warmer, external environment and the MVD's environment. This will allow technicians a longer time to repair the cooling system(s).

This lower heat transfer rate is accomplished by the Rohacell foam that provides the structure for the RF shielding foils. Rohacell has a thermal conductivity of 0.03W/mK. The outer Rohacell cover is 0.25" thick, which gives it a heat transfer resistance value roughly equivalent to one inch of wood. The inner Rohacell cover is only half as thick at 3mm and therefore has only half of the heat transfer resistance. However, the surface area that is in contact with the external environment is only approximately 1/6th the area of the outer Rohacell cover, so the total heat transferred in via the inner cover is approximately 2.88 times the heat transferred in via the outer cover assuming the same environmental conditions. All told, the heat transfer through the exposed Rohacell-supported surfaces of a fully assembled MVD is close to the heat transfer through a 23"x23"x0.25" sheet of plywood.

Section 4: Building the Inner RF Enclosure

4.1 Thermoforming properties of Rohacell IG-71

Rohacell is a closed-cell rigid expanded plastic material, or more accurately, a polymethacrylimide rigid foam (PMI). It has excellent mechanical properties, high dimensional stability under heat, solvent resistance, and a low coefficient of heat conductivity. Its strength, modulus of elasticity, and modulus of shear are not exceeded by any other foamed plastic having the same density.[9] See Table 4-1 for comparison of Rohacell's properties with other materials.

Table 4-1: Physical Properties of Structural Support Materials

	Density (kg/m^3)	Tensile Strength (MPa)	Compressive Strength (MPa)	Elastic Modulus (GPa)	Thermal Conductivity (W/mK)	Radiation Length (m)
Rohacell IG-71[a]	75	2.8	1.5	0.092	0.03	5.45
Pine Wood[b]	300 - 900	40 - 190	30 - 80	9 - 16	0.12[c]	—
Poly-styrene[d]	60	1.6	0.9	0.033	0.03	—

a. Rohacell Technical Information pamphlet, page 5
b. CRC Mechanical Engineer's Handbook
c. 2.51 book
d. Rohacell Technical Information pamphlet, pages 12-14

Rohacell is fabricated in flat sheet form in various thicknesses and sizes, but the RF enclosure requires that the Rohacell be in a hemi-cylindrical shape. There are two processes that will obtain the correct shape: 1) thermoforming or 2) machining layers that have been glued together. The least expensive and least wasteful of material is the thermoforming procedure.

Thermoforming Rohacell is a process which raises the temperature above

9. Rohacell technical information pamphlet. Rohm Tech Inc., Malden, MA.

the dimensional stability point and starts breaking the chemical bonds that hold the Rohacell together. While the material is above that temperature, it can be formed into just about any shape so long as the bending radius is more than twice that of the thickness[9]. When the material is cooled down to below the dimensional stability point, the structural bonds reform, and the material retains the new shape with approximately the original physical properties.

During the summer of 1997, tests were performed to accurately determine the relationships between the thermoforming temperature, time, pressure, and method to help find an acceptable and reliable procedure which could be used to thermoform the RF enclosure. The PHENIX technical document[10], "Thermoforming Rohacell for the MVD's Radio Frequency Enclosure", was written to summarize the setup, testing procedures, data collected, and conclusions drawn from the tests, and it has been included in Appendix 2.

The results of these tests indicated that the amount of springback, i.e. the tendency of the Rohacell to return to its pre-thermoformed shape, can be reduced by lowering the cooling rate. The results also indicated that higher pressure of the thermoforming fixture on the Rohacell during the cool down process helps to reduce the amount of size growth.

Size growth occurs when the Rohacell reaches the foaming temperature[10], i.e. the temperature at which the chemical bonds are weak enough that the pressure of the gas inside the foam cells causes the cells to expand. Unfortunately the foaming temperature is only approximately 10 C above the forming temperature, so it is difficult to avoid foaming altogether, but the size growth can be controlled by the amount of pressure applied through the thermoforming fixture.

4.2 The Inner RF Enclosure Thermoforming Procedure

10. PHENIX-MVD-98-27, PHENIX Note 356

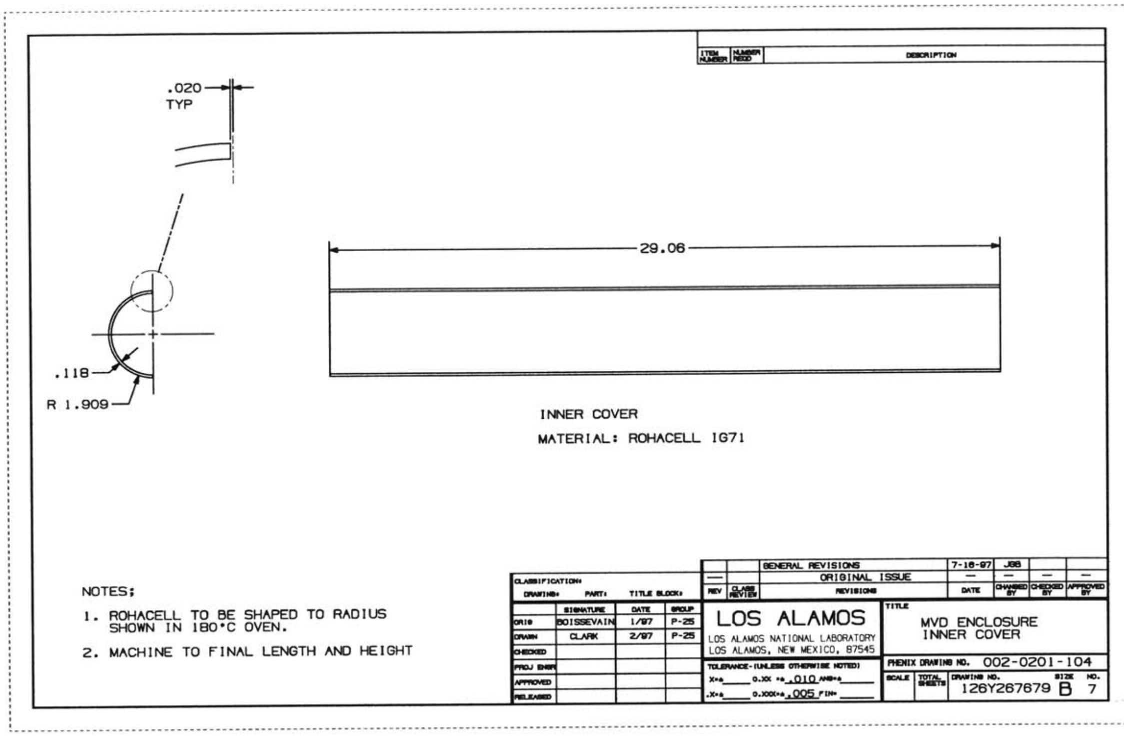

Figure 4-1: The inner RF Rohacell cover

For the particular application of thermoforming Rohacell for the inner structural piece of the RF enclosure (see Figure 4-1), the tolerances on its final shape are tight. As can be seen in Figure 4-2 below, the MVD is designed so that there is only a 5.4mm gap between the surface of the Rohacell and the 1mm thick beryllium beam pipe, and only a 3.35mm gap between the other Rohacell surface and the inner barrel of silicon strip detectors. For the integrity of the experiment and the MVD, no part of the MVD is allowed to touch the beam pipe, and the MVD management does not want any part of the inner RF enclosure to touch the silicon strip detectors for fear that the contact might affect the detectors' operation. Therefore, even though the curved edges of the inner Rohacell cover are fixed into position, any springback must be avoided to keep the free section of the inner Rohacell's straight edge from bowing out to touch the silicon strip detectors.

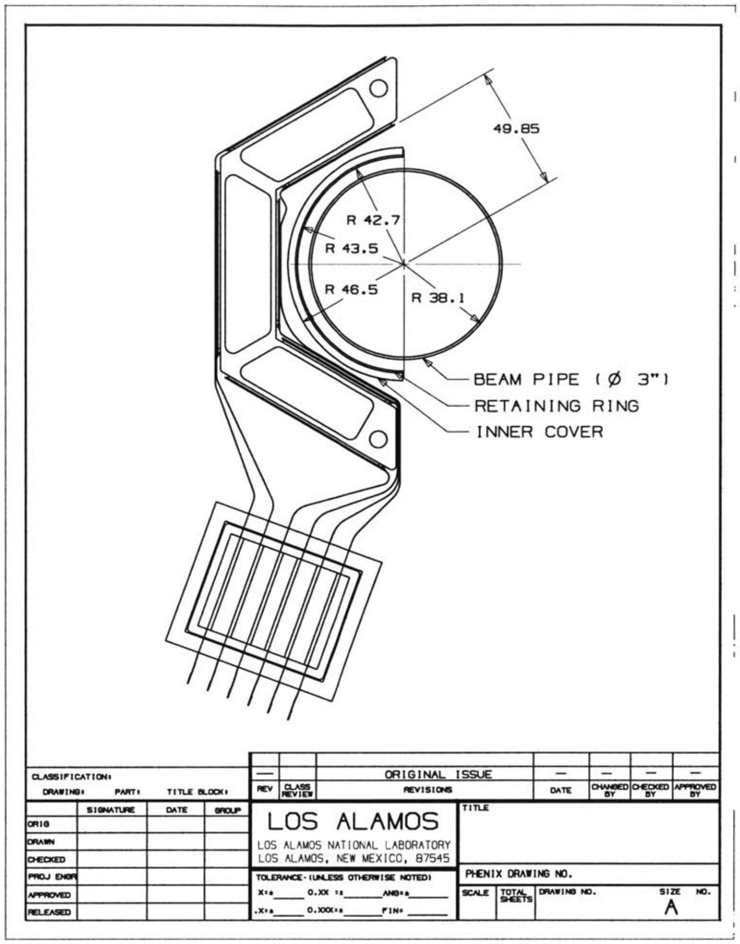

Figure 4-2: Clearances around the inner Rohacell cover

However, these tolerances can be met. In addition to the 1997 tests, some tests were completed in June of 1998 in cooperation with the Rohacell manufacturer's pamphlet. The results helped to show that the required tolerances for the inner hemi-cylinder of Rohacell can be met using the thermoforming materials and procedure delineated in the PHENIX technical document[11], "Fabricating, Assembling, and Installing the Inner Radio Frequency Enclosure of the Multiplicity Vertex Detector", which has been included as Appendix 3.

The springback and thickness growth values for the two 1998 tests utilizing the procedure found to produce the best results are tabulated in Table 4-2 below.

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Table 4-2: Results of Tests Using the Final Thermoforming Procedure

	Avg. % change in radius	Avg. % change in thickness	Total amount intruded into safety gaps (mm)	Avg. % safety gaps intruded on
Test #6	0	8.56	0.13	3.10
Test #7	0	7.18	0.11	2.60

The average percent change in radius is the measure of the springback converted into useful dimensions. It was measured by comparing the cooled Rohacell's radius with the radius of the forming fixture. Zero percent springback means that the thermoformed Rohacell has the exact radius that it should have, and therefore there should be no bowing in the straight edge that could touch the silicon strips. The average percent change in thickness was determined using eight measurements along the edges of the cooled Rohacell. The safety gaps are imaginary volumes that occupy the space that starts at the surfaces of the Rohacell cover and extend out 1/3 of the distance between them and the silicon strip detectors or them and the beam pipe. The safety gap between the Rohacell and the silicon strips is 1.1mm, and the safety gap between the Rohacell and the beam pipe is 1.8mm. Ideally, the Rohacell will never extend past the safety gap, but for safety's sake there is still 2/3 of the entire gap space left to expand into should the inner enclosure need it. The total amount intruded into the safety gap and average percent of the safety gap that was intruded on show that the chosen thermoforming procedure leaves a fair amount of room for error.

This thermoforming procedure was chosen not only because of its size growth and springback results, but also for its ease of production. Other procedures were tested and gave acceptable results, but this procedure minimizes the fabrication time (5 total hours; about 0.5 man hours) in drying out the Rohacell, preheating the thermoforming fixture, and cooling down the Rohacell and fixture.

4.3 The Inner RF Enclosure Machining Procedure

The springback and thickness growth tolerances are met by the thermoforming procedure, but the tolerances on the length and width specifications are met by machining the Rohacell after it is thermoformed. If the length of the Rohacell is not controlled, then the force put on the curved ends by the strut assembly of the MVD could cause the entire shield to buckle, which could in turn cause the inner RF enclosure to come in contact with the silicon strip detectors.

Here, machining is used not to refer to the use of a mill or lathe, but rather to a more general use of shop tools in a shop environment. More specifically, the materials needed to machine the Rohacell to the required tolerances are: the thermoforming fixture, low grit sandpaper, an X-acto knife, and a measuring tape. The entire procedure is delineated in the inner RF enclosure technical document already mentioned, Appendix 3. Using the procedure, the Rohacell can be machined to specifications in a reliable and efficient manner. For an experienced worker, the entire process takes approximately 20 minutes. The procedure is better done in-house rather than out-sourcing to a machine shop, because it uses the thermoforming fixture as a precise guide for straightness in cutting and as a length model for cutting to the exact arc length needed. The thermoforming fixture also serves as an excellent device for holding the Rohacell in the desired position without crushing it.

4.4 The Inner RF Enclosure Assembly Procedure

The inner enclosure assembly procedure, also described in Appendix 3, involves: 1) adhering the RF shielding foils to Mylar foils to increase the tensile and puncture strength and to make the enclosure more air tight, 2) cutting the laminates to the correct dimensions, 3) adhering the foil laminates to themselves, and 4) adhering the laminates subassembly and another Mylar foil to the Rohacell for structural strength. The procedure takes a fair amount of time and experience to perform correctly, but it results in a robust, durable, effective RF shield.

The first step is adhering the shielding foils to the Mylar foils. The 0.5mil sheets of aluminum foil that provide most of the shielding effect have an adequate tensile strength but are very easy to puncture or tear, and because any tears have large stress concentration factors associated with them, they will propagate through the entire sheet once they have been started. But if a thin sheet of Mylar is adhered, then the resulting laminate is fairly robust and durable.

Also, the Mylar provides a tighter air seal than the aluminum foil, and therefore is needed especially at the edges that are used in conjuction with the O-rings. The adhesive used to hold the foils together is Dielectric Polymers' NT 988-2 dry transfer adhesive. It is a 2mil thick adhesive that is delivered in large rolls. Each layer of the adhesive is separated by an extremely non-stick, silicon coated paper. This paper is one of the only materials that the adhesive does not violently stick to, which makes handling the adhesive difficult.

The addition of the Mylar was a significant change to the original RF shielding design. It added several new layers of material to the design, and this added material also added mass, and that mass did not provide very effective RF shielding per unit mass, and so was avoided as much as possible.

However, because the aluminum foil was extremely hard to protect during the assembly and installation procedures, and because the added layers only added 0.06% of a radiation length to the detector, the design changes were implemented.

The completed assembly is comprised of ten layers: three layers of 0.5mil thick Mylar, four layers of 2mil thick NT 988-2, two layers of 0.5mil thick aluminum foil, and one layer of 125mil thick Rohacell foam (see Figure 4-3).

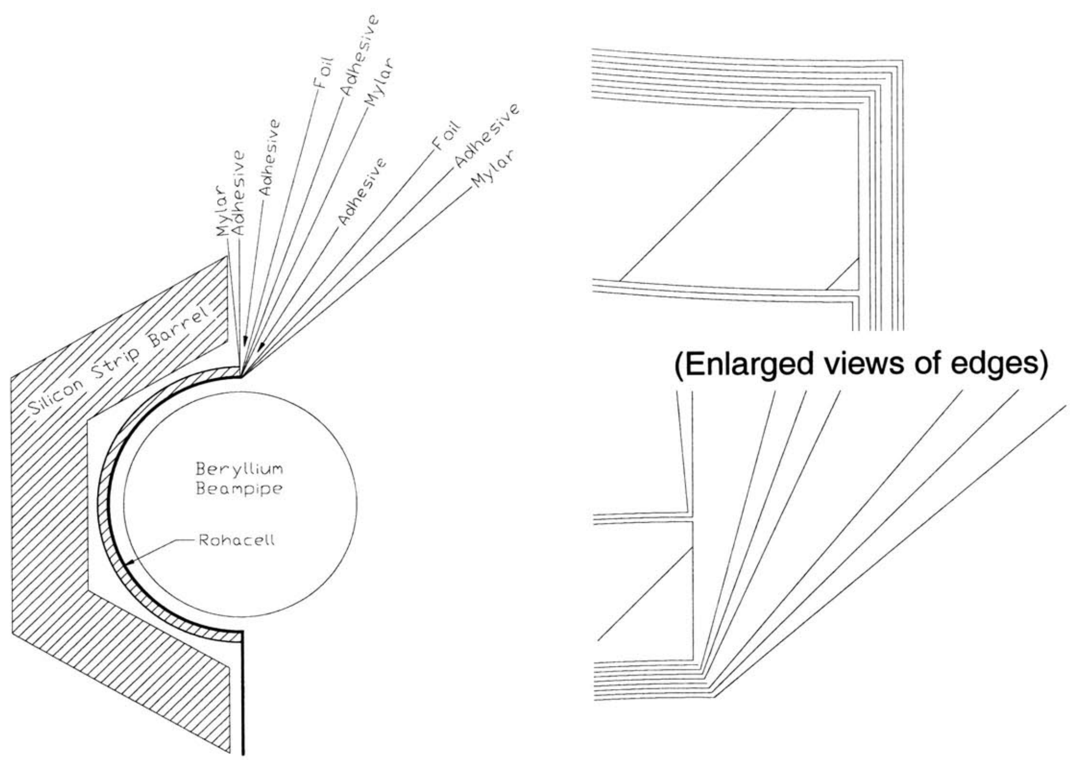

Figure 4-3: Layers of the inner RF enclosure

The second step in the assembly process is cutting the laminates to the correct dimensions. This is a fairly simple step, because the dimensions have fairly loose tolerances. The laminates are constructed to have plenty of extra area to account for any mistakes in the first step made around the edges. This extra will be cut off when the laminates are installed into the rest of the MVD. The only portion of the laminates that must be cut carefully is the area that will be adhered to the Rohacell cover. This area has a tolerance of about 1/16", which is easily attainable using the aluminum cutting template so that there is no measuring needed.

The third step is adhering the laminates together. To increase electrical shielding, the two aluminum foils must be electrically separated. Mylar is a polyester, which has a high volume resistivity ($10^{18}\Omega$cm), and therefore makes a good enough insulator to separate the foils. The laminates are held together with the NT 988-2 dry transfer adhesive, and are only attached together on the surfaces that will be positioned around the beryllium beam pipe in order to minimize the mass added as well as reducing the assembly and installation times.

The fourth and final step is adhering the laminates subassembly to the Rohacell cover and then adhering a final sheet of Mylar to the uncovered side of the Rohacell. The laminates are adhered to the surface of the Rohacell that is nearest to the beam pipe and on the outside of the MVD. This outer surface is used instead of the inner surface in order to make the assembly procedure easier, reduce the chance of the Rohacell absorbing water from the air, and to give the MVD a uniform look. The additional Mylar sheet is adhered to the other side of the Rohacell to ensure that humidity from the air inside the MVD is not absorbed and to ensure that no dust particles from the Rohacell are blown around inside the MVD, which could interfere with the operation of the silicon strip detectors.

Again the NT 988-2 dry transfer adhesive is used to adhere the laminates subassembly and the additional Mylar sheet to the Rohacell. The NT 988-2 is the best adhesive found for the job, and one of the only adhesives found that will stick to the Rohacell at all.

It takes approximately 2.5 hours to complete the assembly procedure for the inner RF enclosure for one half of the MVD. The ten layers give a total thickness of approximately 0.136". If only conduction resistance is considered, the total heat transfer resistance through the surface enclosing the beam pipe is approximately 64W/K. The total radiation length is approximately 0.18%.

4.5 The Inner RF Enclosure Installation Procedure

The inner RF enclosure is one of the last components to be integrated into the MVD. It should be installed after all the structural components, electronics, and outer RF enclosure have been installed, but before all cables and hoses have been attached. After it is installed, there is no way for the electronics inside to be modified without first removing the inner enclosure, and the inner enclosure cannot be removed without destroying it. However, because the fabrication procedure is relatively inexpensive and a new enclosure can be made in a matter of a few hours, the decision of whether to repair or modify any of the electronics is not influenced by the removal of the enclosure.

Because it is installed after all the electronics, the procedure for installation must be very reliable and have an extremely small possibility of damaging the already installed components. However, this constraint is not easily met due to the force required to lay the O-rings into their respective grooves. Depending on how the MVD is held in place, the large amount of force could torque the MVD so much that it overcomes the opposing torque due to gravity, resulting in a crash of dire consequences. Therefore, a fixture is being designed that will securely hold the MVD in a fixed position so that there is no chance of an accident.

The installation procedure for the inner enclosure is documented in Appendix 3. It has two main parts: 1) attaching the hemi-cylindrical Rohacell section to the adapter cuffs of the aluminum D-rings and 2) installing the foil laminates in the O-ring grooves and trimming off the extra. With the experience of just a few installation trials, the whole process takes on the order of one hour to complete, but it requires two people during the O-ring installation steps.

The first part is straightforward and simple. The Rohacell with attached laminates must be adhered to the half-MVD's aluminum frame, which is a subassembly that consists of four aluminum D-rings (so named for their shape), four thin aluminum endplate shields, two aluminum adapter cuffs, and two hollow, cylindrical, aluminum struts. In order to precisely locate the inner Rohacell cover the two adapter cuffs are precisely and permanently fixed to the D-rings, and then the inner RF enclosure assembly is adhered to the cuffs and pressure is applied by four aluminum retaining rings to hold them in place.

The next step is to push the foil laminates into the O-ring grooves. This is most easily accomplished with the help of a spline tool. A spline tool is a tool specifically made for this purpose. It is a handle with one roller on each end. One roller helps to crease the screen or foil into the groove, and the other is made to press the O-ring into the groove without allowing it to slide around. The spline tool that was used was very generic, and therefore had to be modified to the correct dimensions using a lathe. The thickness constraint was determined by the size of the O-ring grooves, and the wheels were machined with a small radius so that they do not buckle under the force.

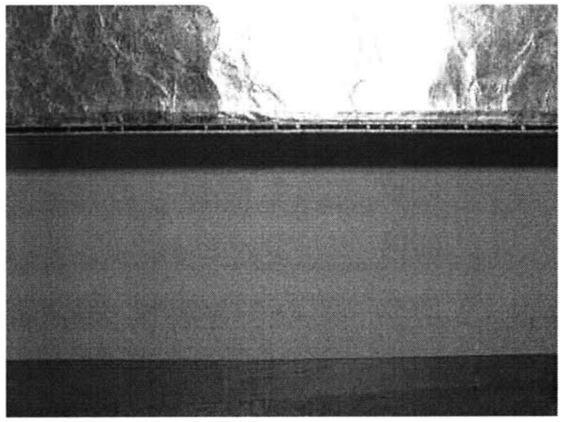

Figure 4-4: Cracked Buna-N O-ring material in inner enclosure mock-up

The O-ring material used is urethane. The original material was Buna-N (nitrile), which is a much more universally used and cheaper O-ring, but after little more than a month of being installed with the foil laminates in the D-rings in a mock-up of the MVD frame, it was found that the Buna-N was severely cracking. This can be seen in Figure 4-4 above. One manufacturer and one distributor of O-rings were contacted for advice and suggestions. One suggestion was that the ozone in the air was causing the cracking, but that potential explanation was quickly ruled out. A test was performed to determine the cause of the Buna-N's cracking as well as to test another O-ring material, urethane, for the same behavior. The Buna-N was subjected to several independent combinations of the environmental elements that were present while it was inside the O-ring grooves. The elements combined were tension, contact with aluminum foil, contact with Mylar, and contact with the NT 988-2 adhesive. Also, the urethane was put under tension and in contact with the adhesive. The tests were conducted over three months.

Only the O-ring strips that were put under tension and in contact with Mylar and those that were under tension and in contact with the dry adhesive showed the cracking that the O-ring strips in the MVD mock-up showed. Based on those observations, more precisely controlled tests would have to be performed to have meaningful results. No decisive conclusions were drawn about the cause of the cracking, but since the urethane showed no signs of cracking, the decision was made to use urethane instead of taking a chance with Buna-N.

Once the O-rings are in place, the only thing left to do is cut off the extra laminate strips. This is an easy step, but care should be taken, especially at the corners, not to tear or puncture the laminates in any vital area. If any tears or holes are made in the vital areas of the aluminum foil during any step of the installation, then the enclosure should be scrapped and a new enclosure installed.

Many inner enclosures will need to be fabricated during the lifetime of the MVD. At least one needs to be installed during testing of the MVD at the Los Alamos facilities, several others need to be shipped separately to the PHENIX experimental hall, one needs to be used during the MVD's tests at Brookhaven, one needs to be installed before the MVD is installed in PHENIX, and then at least one is needed for every time the MVD is repaired or modified after that. Since there is no disadvantage (besides losing storage space) to fabricating several extra inner enclosures before they are needed, the same person should make several within a short time period to ensure accuracy and uniformity between the enclosures.

Section 5: Building the Outer RF Enclosure

5.1 The Outer RF Enclosure Thermoforming Procedure

The thermoforming procedure for the outer enclosure is very similar to the procedure for the inner enclosure. The Rohacell must be cut to the approximate size needed and then dried out. Then it can be aligned in the thermoforming fixture, which will hold it in its post-thermoforming shape while it is thermoformed and then cooled.

It is possible to hold the cold Rohacell in its post-thermoforming shape because the final radius of curvature is large enough that bending a flat sheet to that radius will not impose a stress higher than its maximum tensile or compressive yield stress. The curvature of the thermoforming fixture is circular, but the curvature of the bending Rohacell is the same as that of a cantilevered beam and varies proportionally to the cube of the distance from the fixed end. When the Rohacell is forced around the fixture, it touches the fixture where the natural cantilevered beam deflection equals the deflection of the fixture's curvature. The intersection of the curves in Figure 5-1 shows the point where the deflections are equal.

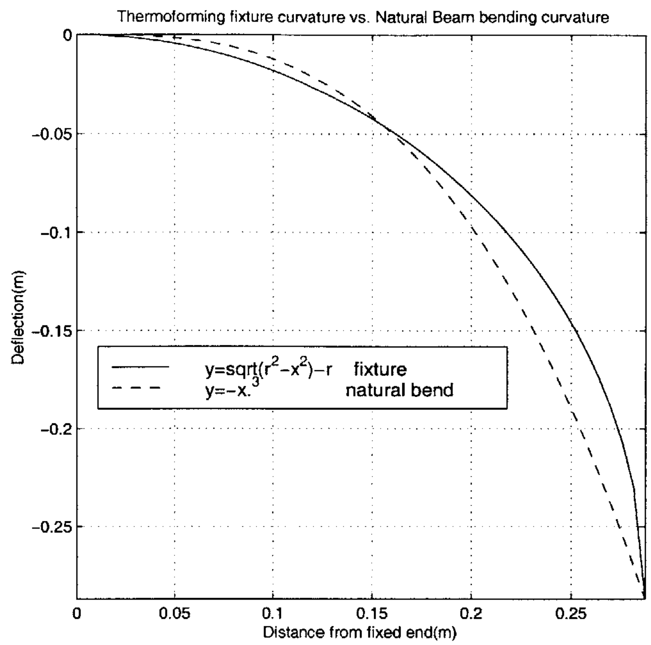

Figure 5-1: Thermoforming fixture vs. Rohacell bending curvatures

When it touches the fixture, the working length of the Rohacell is shortened by the arc length of the fixture to that point. By shortening the working length, the moment on the beam is decreased, which keeps the stresses in the Rohacell from going above its yield stress.

The thermoforming fixture was designed to provide a generally uniform heat flux into and out of the Rohacell. It consists of a 0.0625" thick sheet of aluminum, four 0.25" thick aluminum ribs which hold the sheet in the correct shape, and several small parts which help to rigidly hold the fixture together. The ribs were machined by clamping four 0.25" aluminum plates together on a rotating chuck that was fixed to the milling bed. The chuck was offset so that the milling bit cut all the aluminum plates to the same correct radius as the chuck was rotated, and holes were drilled through all four plates so that struts could be used to offset the plates from each other without changing their relative axial position.

After the Rohacell is placed into the forming fixture, the temperature of the fixture is increased to and kept at the thermoforming temperature (approximately 185 C) until all the chemical bonds in the Rohacell have relaxed. Then the temperature is slowly decreased until all the bonds have reformed. At that point the Rohacell can be removed and put in storage until it needs to be cut to the exact dimensions. This procedure is detailed in Appendix 4: Fabricating, Assembling, and Installing the Outer Radio Frequency Enclosure of the Multiplicity Vertex Detector[12].

The tolerances for the thickness growth and springback of the outer Rohacell cover are determined by the strain imposed on the shielding foil covering the Rohacell and by the distance between the inner Rohacell cover and the silicon strip detectors, respectively. A conservative estimate shows that the thickness growth cannot be larger than the twice the initial thickness of the Rohacell cover multiplied by the ultimate tensile stress of the foil divided by the Young's modulus of the RF shielding foil (see Equation 5-1 below), or else the foil will tear and produce a hole that high frequency RF radiation can leak into. Calculation of the maximum tolerable thickness growth gives a result of 2.7mils for a maximum final thickness of 0.2527".

$$\text{Thickness Growth}=t_f - t_i \quad ; \quad \varepsilon_{foil} = \frac{1}{2}\left(\frac{t_f - t_i}{t_i}\right) \quad ; \quad \varepsilon_{max} = \frac{\sigma_{ult}}{E} \quad ; \quad t_f - t_i < \frac{2 t_i \sigma_{ult}}{E} \qquad \text{(Eq. 5-1)}$$

The maximum springback growth is more difficult to determine analytically, because the cylindrical shape leads to a non-obvious working length, the end constraints are not easily defined, and there are two thin aluminum strips installed into the straight edge the have grooves for the O-rings that help resist any springback. The maximum springback also depends on the amount of tension used to install the inner enclosure's foil laminates into the O-ring grooves in the straight edge of the outer enclosure. Because of the difficulty in solving a detailed model, a very conservative estimate was made that the springback should be less than 1/8th of the distance between the edge of the inner Rohacell cover and the edge of the silicon strip detectors, or less than 0.035".

Although the calculations would be difficult, the idea is not hard to grasp. If the springback of the outer Rohacell cover is negative, i.e. the straight edge bends in towards the central axis, then there is probably not going to be a problem. But if

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the Rohacell springback is positive and during the inner enclosure installation the Rohacell is force into a straight shape, then the springback will pull on the laminate foil layers of the inner RF enclosure. If the force pulling on the laminates is strong enough, then the laminates will pull the inner Rohacell cover into the silicon strip detectors, which must be avoided.

If the installation procedure for the inner enclosure installation is followed precisely, then the laminate foils will be cut to match the curvature of any springback, and there will be very little tension on the laminates. However, if any force is put on the outer enclosure to straighten out the springback, or if tension is put on the laminates when they are installed into the O-ring grooves, then that force and/or tension will remain after the installation. This in turn will pull on the inner Rohacell cover, which is approximately eight times weaker than the outer RF cover due to its smaller thickness. Because the inner cover is approximately eight times weaker, the pulling force will impart a deflection of its straight edge that will be approximately eight times larger than the outer enclosure's deflection, so any small force on the outer Rohacell cover will cause a large springback in the inner Rohacell cover (see Equation 5-2 below).

$$h_{outer} = 2h_{inner} \; ; \; I = \frac{bh^3}{12} \;\Rightarrow\; I_{outer} = 8I_{inner} \;\Rightarrow\; \delta_{outer} = 8\delta_{inner} \qquad \text{(Eq. 5-2)}$$

Tests were done during the fall of 1998 to determine the parameters for a thermoforming procedure that would meet the required tolerances for springback and thickness growth. Out of the eight outer Rohacell covers fabricated, two exceeded a positive average springback of more than 0.035" (they were 0.05" and 0.11"). For thickness growth, one of the eight covers had a positive average growth over 2.7mils (5.5mils). Barring those test specimens the procedures tested gave results within the defined tolerances, and the parameters chosen for the final procedure are listed in Table 5-1 below.

Table 5-1: Properties of outer enclosure thermoforming tests

Drying Time	Drying Temp	Forming Time	Forming Temp	Cooling Time	Average Thickness Growth	Average Springback
180min	120 C	30min	185 C	45min	-2.2%	-3.6mm

5.2 The Outer RF Enclosure Machining Procedure

Once the outer RF enclosure is thermoformed within the specified tolerances, it must be cut to exact dimensions. This involves three steps: cutting the length to specification, cutting the width to specification, and then milling out the seal strip grooves. The length is the distance around the curved portion of the Rohacell, and it must be cut to within approximately 1mm of its nominal value at the corner edges to ensure that the O-ring grooves flow smoothly from the D-rings to the seal strips and back into the other set of D-rings. The width is the distance from one of the curved edges to the other, and it must be cut to greater than 28.81" but less than 29.06" in order to keep the enclosure correctly situated on the D-rings. The seal strip grooves are grooves that have to be milled into the straight edges of the Rohacell for the aluminum seal strips. The seal strips are machined to very tight tolerances, and the Rohacell must be milled so that the seal strips fit snugly into the grooves without putting too much force on the thin Rohacell edges. The exact dimensions of the outer enclosure are shown in Figure 5-2 below.

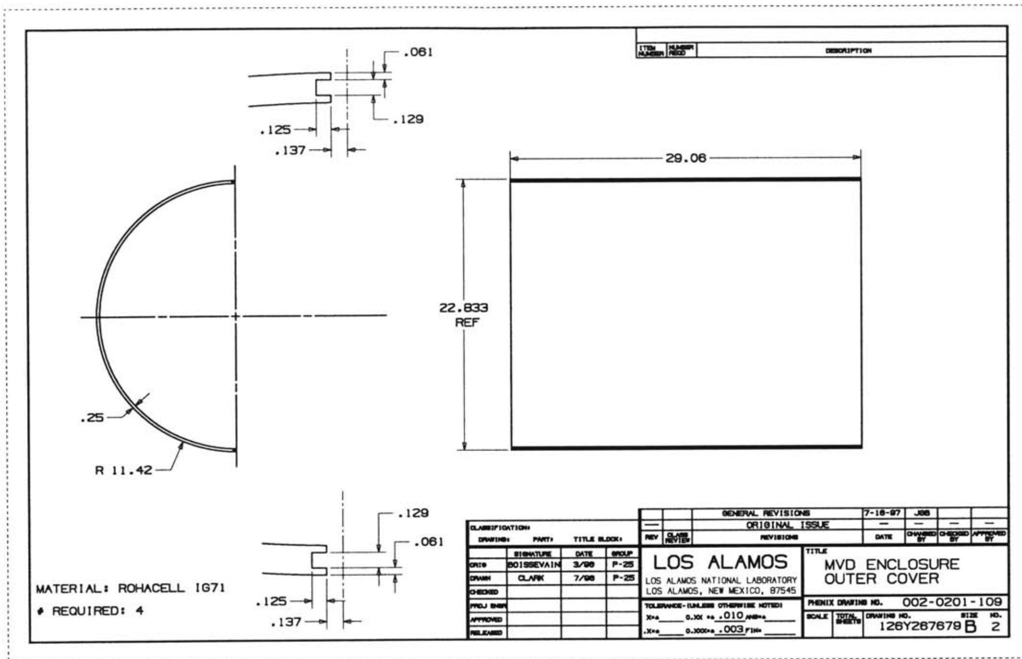

Figure 5-2: The outer Rohacell cover

Even though the tolerance of the length is fairly tight, it can still be met using a razor blade and fixtures. The first fixture is simply a precise mock-up of the D-rings and strut assembly. With the Rohacell positioned correctly in the D-rings, marks can be made which precisely show what the width of the finished outer enclosure should be. The marks can then be used in conjuction with another fixture to precisely cut the Rohacell to the width marked. This process is neither difficult nor time consuming. It should take an experienced person about 30 minutes to cut one half-cover to specification.

The width tolerance is loose, and can also be met using a razor blade, sandpaper, and a fixture. Because the Rohacell is already cut to the correct length, it can be aligned by those edges in the correct orientation. Using the fixture to hold it in place, the Rohacell can be rough cut to the correct width with a razor blade, and then sandpaper used to bring it to the exact dimension.

Once the length and the width are cut, a seal strip groove needs to be milled into both straight edges of the Rohacell cover. The groove thickness must be machined to within a few mils of the nominal dimensions so that the seal strips will fit snugly; therefore, a mill must be used. And because the length of the cover is almost 30", a mill with a long travel distance bed must be used. The milling bit's axis should be horizontal instead of vertical, because the shape of the Rohacell cover requires that if a vertical axis mill was used, then an intricate fixture that was extremely well stabilized would have to be designed and constructed and a mill with a large vertical travel as well as horizontal travel would have to be used.

Upon procurement of the use of a horizontal axis mill, a machining fixture was designed and fabricated to hold the Rohacell in place on the milling bed (see Figure 5-3a, b, and c below).

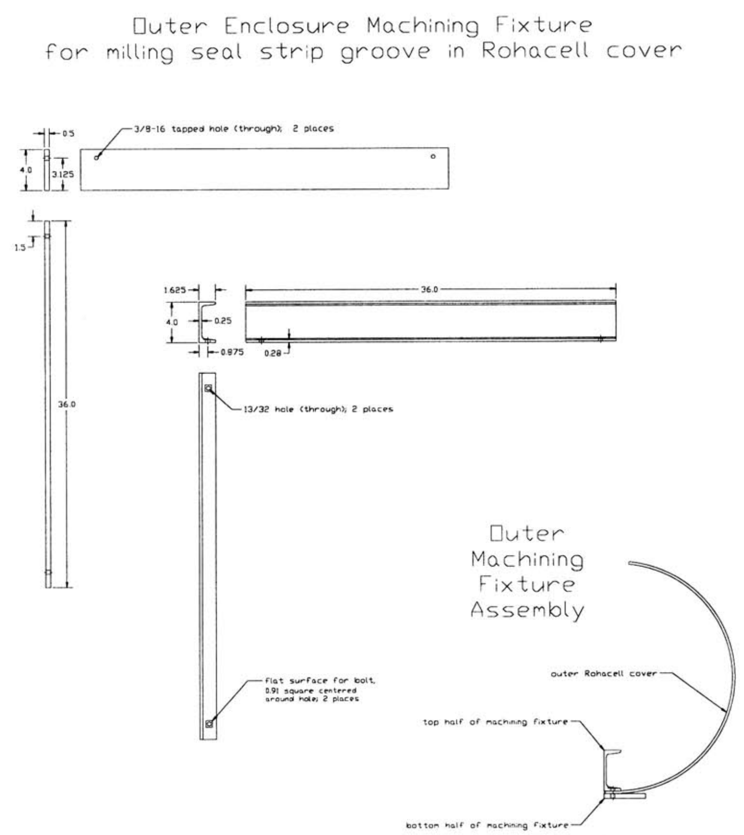

Figure 5-3a: Base plate, top plate (C-beam), and assembly,

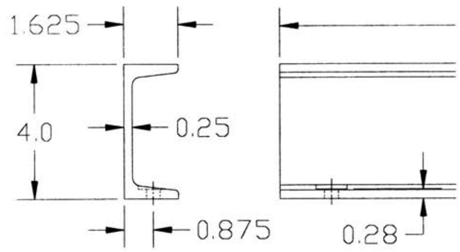

Figure 5-3b: Enlarged view of top plate (C-beam)

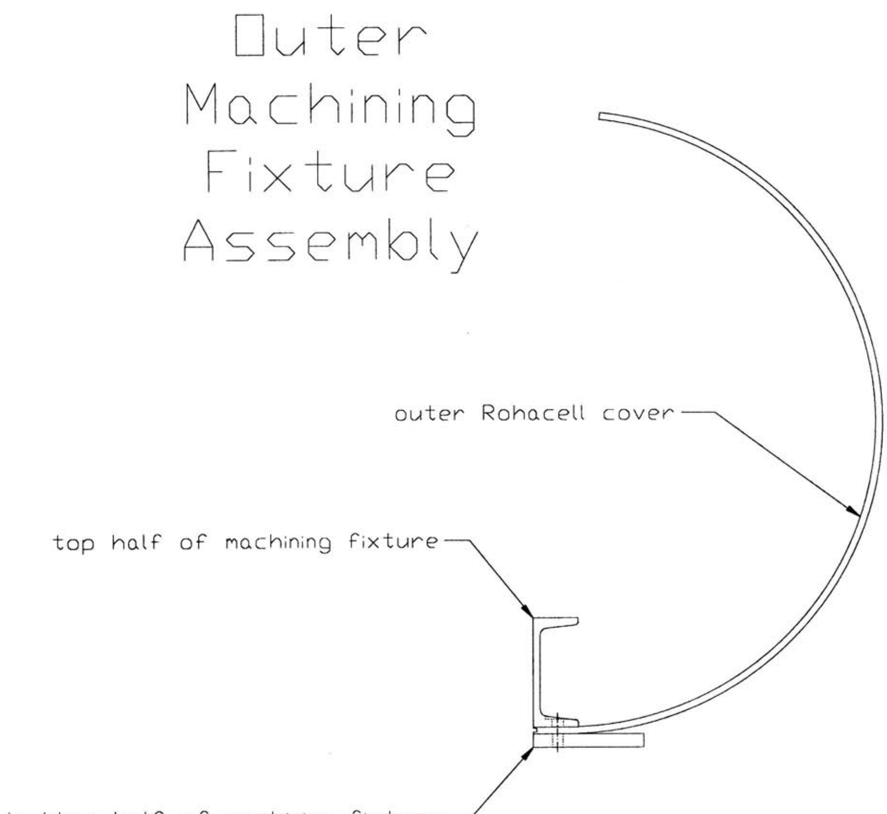

Figure 5-3c: The outer cover machining fixture assembly

The design consists of two main parts, the base plate and a top plate. The base plate is flat and rigid to provide a reference surface for the mill to align with. The top plate is a C-beam (half of an I-beam), and provides a high vertical stiffness so that the force of the bolts used to clamp the top plate to the base plate is distributed along the entire width of the Rohacell. The design minimizes the complexity with just four parts (top plate, base plate, and two bolts) and thereby minimized the expense of time and money to fabricate it.

The milling procedure requires that a vertical reference point be found once by touching the base plate to the milling bit at several points along its width. Then the Rohacell sheet is bolted in place in the machining fixture and the base plate is set to the correct vertical position and the milling bit is run along the width of the Rohacell. Because the bit used to mill out the foam is not exactly the same diameter as the desired thickness of the seal strip groove, the bed's vertical position is then changed to mill out the extra foam, and the bit is run back along the width for the final cut. After one groove is milled, then the Rohacell is taken out of the fixture, flipped over, and placed back into the fixture to mill out the other groove.

The milling machine used to machine the Rohacell cover test specimens was fairly old and not very accurate. As the bed travelled horizontally from one extreme to the other, the vertical position of the bed relative to the milling bit was shown to change by approximately 10mils. There was also another vertical error that did not show up on the digital positioning readout and was not consistent over the tests. It varied from no error to approximately 40mils. It did, however, seem to be consistent while the Rohacell was bolted in place, so that the groove maintained the desired thickness. Due to time constraints, the exact reason for the error was not thoroughly investigated; however, it was reasoned and tested that even the largest error that was produced could be tolerated and did not significantly effect the ability of the enclosure to provide RF shielding, humidity and temperature isolation, structural protection, or a secure hold on the seal strips.

Once the milling is finished, the handler should be extremely careful with it, and avoid touching the grooved, straight edges. Each groove makes two thin "lips" of Rohacell, which have a length of 132 mils and vary in thickness from 28mils to 88mils depending on the amount of vertical error in the positioning of the mill relative to the milling bit. These lips are very fragile and could easily be crushed by grabbing the enclosure or by bumping the edge into a hard surface.

If all the equipment and tools are set up, then the entire machining procedure for one outer RF enclosure, consisting of cutting the length and width and milling the groove, takes an experienced person about 90 minutes to complete.

5.3 The Outer RF Enclosure Assembly Procedure

The assembly procedure for the outer RF enclosure is simple, although more skill and helpers are needed for the job than for the inner RF enclosure. It consists of three steps: 1) adhering an RF shielding foil to the inner surface of the Rohacell, 2) adhering another RF shielding foil to the outer surface of the Rohacell, and 3) inserting the seal strips into their grooves. This procedure is detailed in Appendix 4.

Again, the NT 988-2 dry adhesive is used to adhere the 0.5mil aluminum foil to the Rohacell surfaces, because it provides the strongest adhesion to the foam. The first step is to stick the adhesive to the foil, and then the foil can be adhered to the foam by rolling the foam over the sticky foil. The same procedure can be used to adhere the foil to the inner surface, except a small radius cylindrical rod must be used to roll on the foil. Both steps require at least two people due to the size and awkward shape of the Rohacell. The final step is to push the seal strips into their grooves.

Two main problems can occur while assembling the enclosure: the foil can severely wrinkle, and the foil can easily be ripped. While adhering the foil to the inner surface, there is a tendency for the foil to wrinkle. While wrinkling is tolerable, it is not desired, and if severe enough it can change the attenuation properties of the enclosure. Wrinkling occurs when some areas of the foil overlap other parts of the foil, and this overlap of material can triple the shielding (and mass) of the smooth areas, thereby non-uniformly increasing the attenuation.

Tearing, the second problem, can occur during the assembly or after. Because the outer enclosure does not use Mylar to help increase the foil's strength, it is very fragile even after being adhered to the Rohacell. If a shielded surface is bumped into an edge or rubbed across a slightly rough surface, then the foil will tear and the hole will allow RF noise to pass through the enclosure unattenuated. Therefore, during assembly the handler must take care to avoid any tears, and after assembly the enclosure must be stored in a soft, secure environment until needed for installation.

The entire assembly process for the outer enclosure of one half-enclosure takes approximately one hour to complete. The assembled enclosure has five layers: one Rohacell, two adhesive, and two shielding foil layers. It has a nominal thickness of 0.255", 0.250" of which are the Rohacell foam. If only conduction resistance is considered, the total resistance to heat transfer through the outer enclosure is roughly 0.3W/K. The total radiation length is approximately 0.18%.

5.4 The Outer RF Enclosure Installation Procedure

The outer RF enclosure should be installed after all the other MVD subassemblies except for the inner RF enclosure have been installed. It could be shipped separately to the PHENIX experimental hall at the Brookhaven National Laboratory where it could be kept in a secure environment and then installed after the rest of the MVD has arrived there and been fully tested on the Maintenance Test Stand (MTS). It could also be placed around the MVD during shipping to protect the MVD from damage during transportation and then moved to a secure environment until needed.

The installation procedure is simple and straightforward, and only has one main step. The enclosure must be aligned with the D-rings so that the O-ring grooves in the seal strips match the O-ring grooves in the D-rings and then it must be fixed in the desired position by screwing the outer retaining rings (see Figures 5-4 and 5-5) into place.

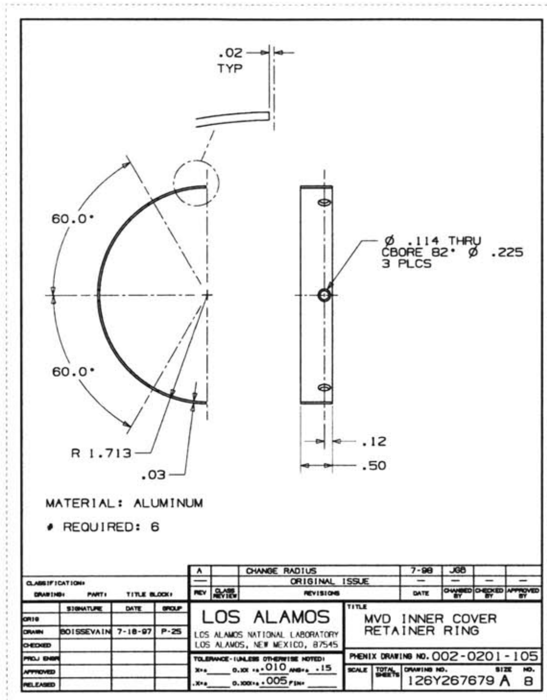

Figure 5-4: The inner enclosure retaining ring

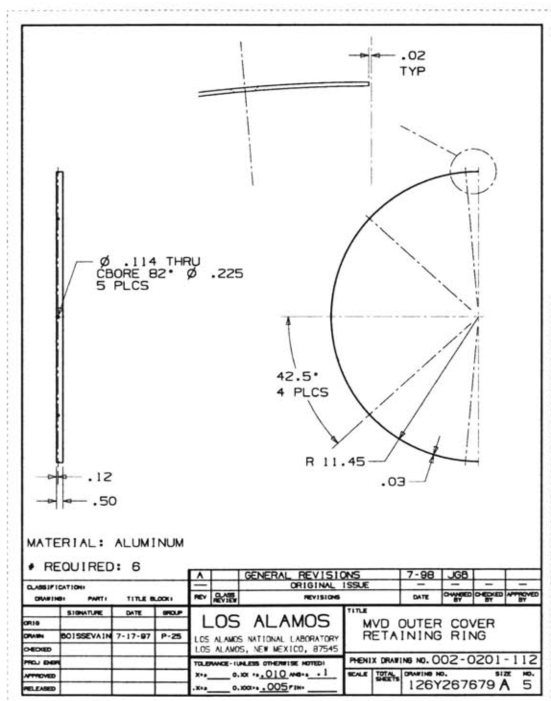

Figure 5-5: The outer enclosure retaining ring

During the installation, the MVD should be held steady and secure in a fixture so that the force put on the aluminum frame from the installation procedure will not move the MVD. As of March 1999 the fixture has not been designed, but a conceptual drawing, Figure 5-6a, b, and c, shows the general idea.

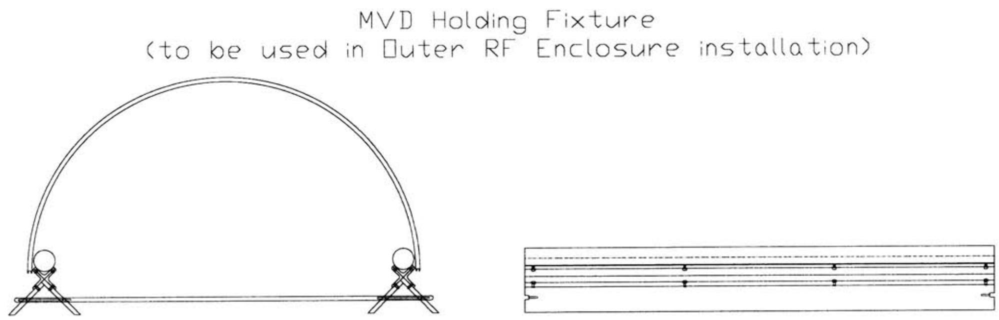

Figure 5-6a: Conceptual assembly drawing of MVD holding fixture

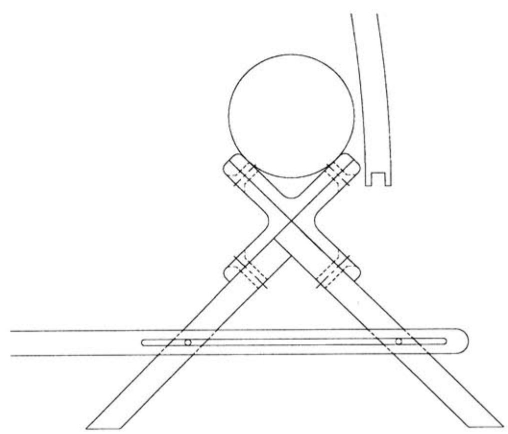

Figure 5-6b: Enlarged end-view with Rohacell and strut in place

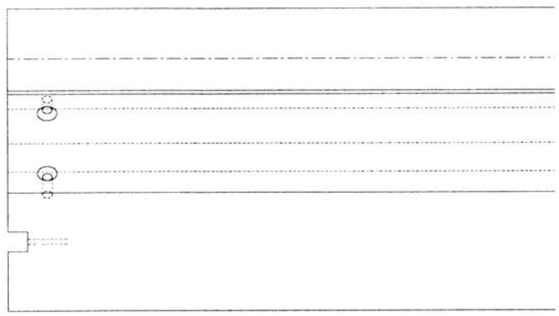

Figure 5-6c: Enlarged side-view of holding fixture

The fixture will cradle the MVD so that the flat surfaces parallel with the beam axis are also parallel with the table where the assembly will occur. It will grab the aluminum struts only so that any chance of contact with the silicon strip detectors or the electronics are minimized. It will not interfere with the installation of the outer enclosure, so that it will not complicate the installation procedure or damage the enclosure. And it will allow for safe, easy, and reliable transportation of the MVD back and forth from the MTS to the assembly table.

The entire installation procedure has not been tested with the real MVD, Maintenance/ Test Stand, or holding fixture, because those parts have not been constructed yet. However, the installation procedure detailed in Appendix 4 has been tested several times using a mock-up of the MVD's aluminum frame that has the same dimensions but is missing the central detector barrel and electronics in the endplates. These differences in the setup should not significantly affect the procedure, especially in this simple case. The approximate installation time is hard to estimate due to the increased amount of care that must be taken when installing the enclosure into the actual MVD, but taking that into consideration, it should not take an experienced person more than 30 minutes to complete.

One unexpected observation and possible problem in the outer enclosure that was noticed in the practice installations was that in some areas the edges of the enclosure were not thick enough to be firmly held in place by the retaining rings. However, this should not pose a threat to its functionality. The change in RF shielding should be negligible, because the radiation length of the Rohacell is very high, so any difference in thickness will not significantly change the attenuation. Any difference in air pressure from inside the MVD to atmospheric pressure will help to reinforce the air-tightness and humidity seal. The only way the outer enclosure effectiveness could be compromised is if the difference in air pressures was negligible, in which case the seal between the outer enclosure and the D-rings would be weak, and there would be a chance that the outside air could diffuse through the small gaps and affect the environment inside the MVD. See Figure 5-7 below for a graphical explanation.

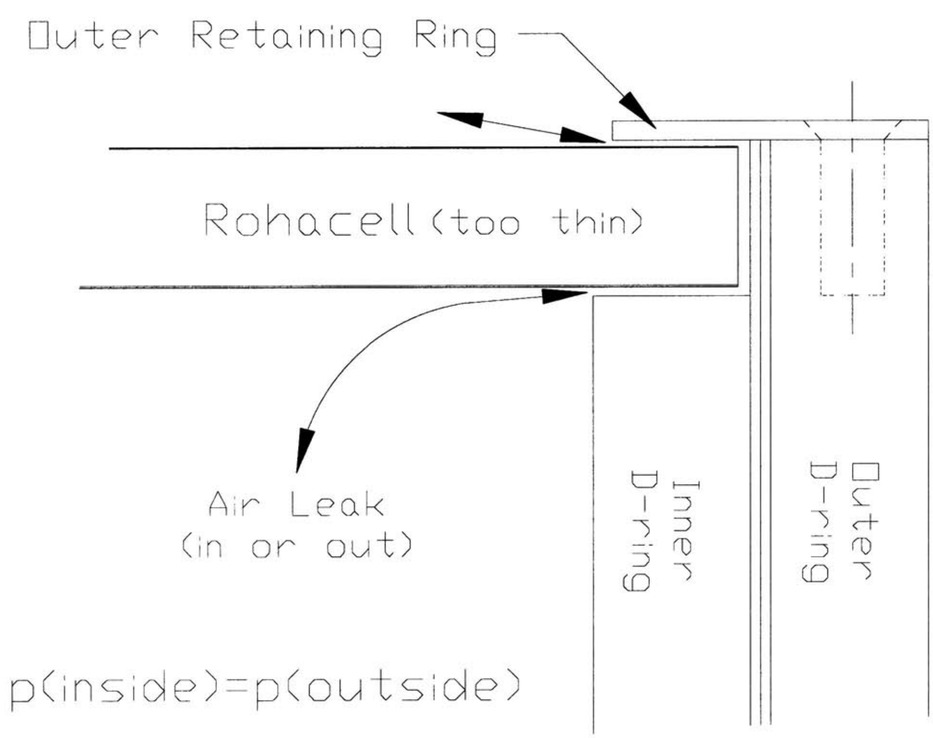

Figure 5-7: Model of possible air leak path

Section 6: Testing the RF Enclosure Prototype

After the assembly procedures for both the inner and outer enclosures were determined, a prototype of the RF enclosure was installed onto a mock-up of the aluminum struts and D-rings that make up the frame of the MVD. This prototype was used put through an RF attenuation test and an air leak test to test its effectiveness.

The prototype used the finished product for the RF enclosure (i.e. a final inner enclosure, a final outer enclosure, urethane O-rings, and the final seal strips), but the mock-up of the MVD frame was not completely accurate. The D-rings used were machined to the same dimensions and tolerances as the real D-rings, but the holes for the retaining ring screws were not drilled or tapped. The struts used were the actual struts. The adapter cuffs that hold the Rohacell C-cages in place in the central barrel detector were not installed. The endplate RF shields were not machined to the exact dimensions, but only to the tolerances required for them to hold the D-rings in their proper position. The D-rings and endplate RF shields were not adhered together, but rather clamped together by small, quickly designed and fabricated, aluminum clamps (see Figure 6-1).

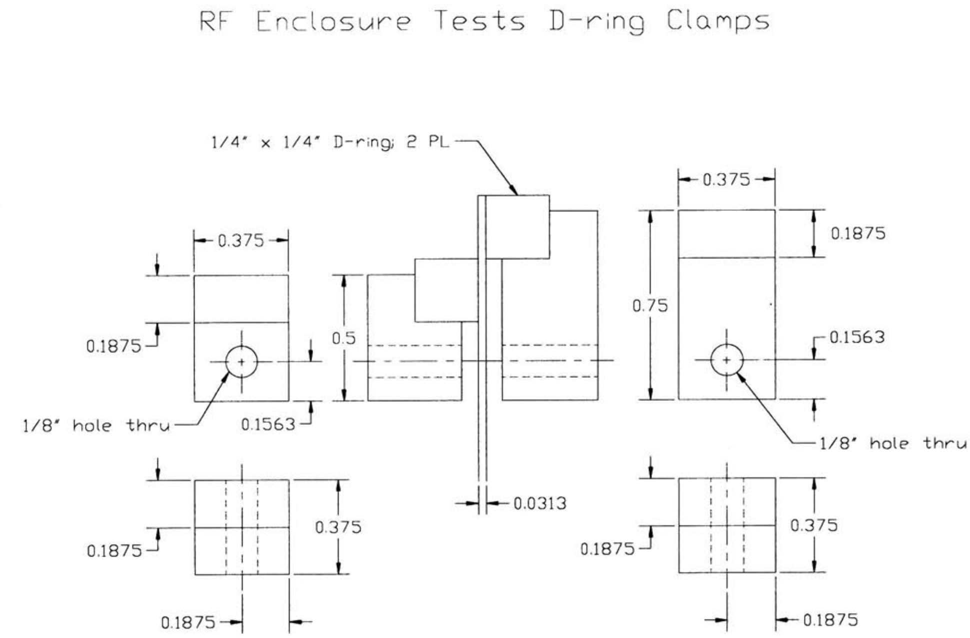

Figure 6-1: Temporary clamps for MVD frame during RF enclosure tests

Even with those temporary parts, the mock-up frame provides the properties of RF attenuation and shape that are needed in order to have meaningful results from the attenuation and air leak tests. The results of both tests were very positive, and the RF enclosure has been deemed worthy of being a part of the MVD.

6.1 Testing the RF Shielding Capabilities

In order to test the RF shielding capabilities of the RF enclosure, tests needed to be run that would measure the magnitude of RF signal attenuation at different frequencies. The broadcast signal was sent through an antenna by an RF signal generator. For the best efficiency of signal transmission, each antenna was cut to 1/4 of the wavelength of its corresponding signal.

The received signal was captured by another antenna and sent via shielded coaxial cable to an oscilloscope. Again, for the best efficiency of signal reception, the antenna's length was cut to 1/4 of the RF wavelength being transmitted. The oscilloscope had a real-time FFT mode which showed the magnitude versus frequency plot for the received signal and background RF noise.

The attenuation of the enclosure was found by measuring the difference between the magnitude of the received signal with the antenna completely unshielded and with the antenna completely shielded by the enclosure. With this setup any difference in signal intensity measured must be a result of the enclosure's shielding properties.

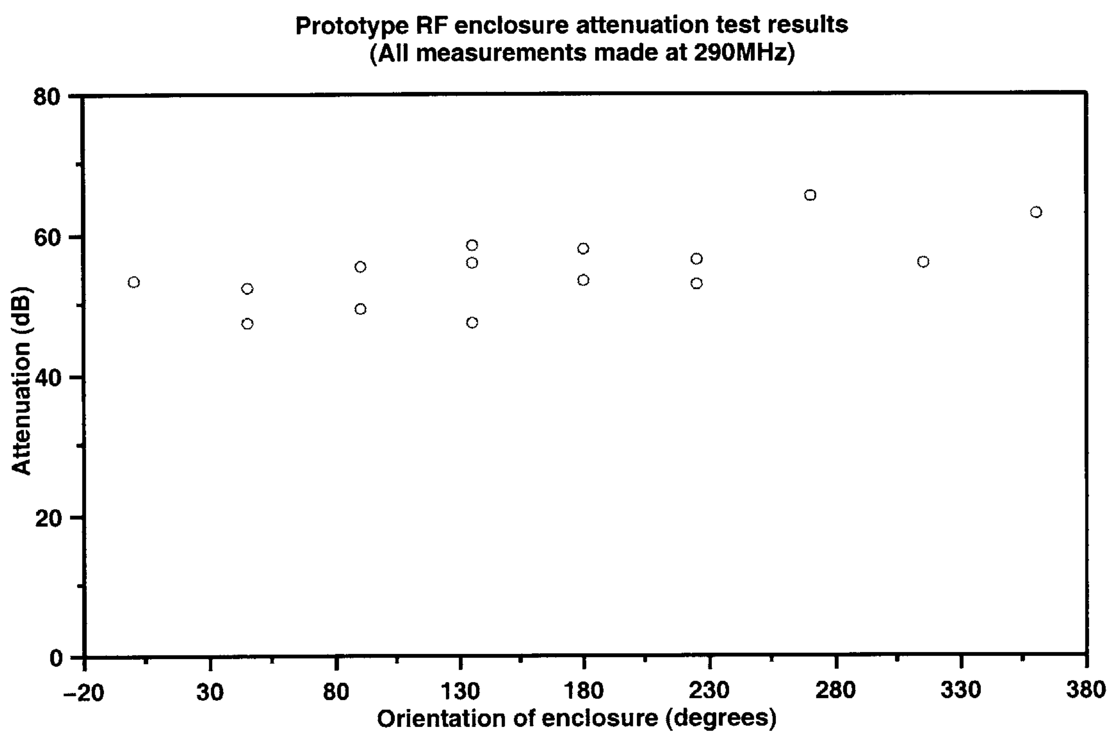

Figure 6-2: Variation of attenuation with enclosure orientation

Measurements of the received signal properties at different frequencies and enclosure orientations were measured. All data recorded during the RF shielding tests can be found in Appendix 5. It was observed that if the orientation was changed and then changed back to approximately the same position, then the attenuation was different, which indicated that the enclosure attenuation changes significantly with even a small change in enclosure orientation. The variation in attenuation can be seen in the plot of the results in Figure 6-2 above.

With the receiving antenna completely inside the RF enclosure and the enclosure position as well as the transmitted signal frequency and magnitude held constant, the received signal intensity was measured for several minutes to ensure a reliable signal was observed and to estimate the amount of error associated with the measurement. Then measurements of the signal magnitude were repeated with the antenna in the same position but with the enclosure removed.

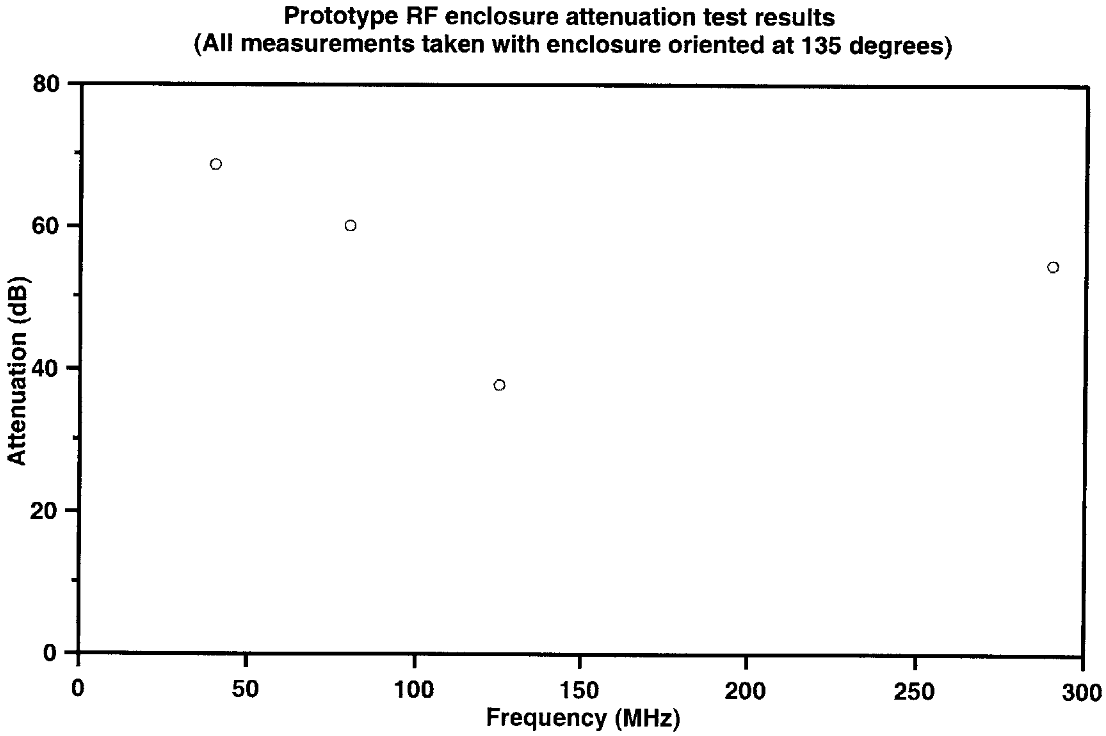

Figure 6-3: Variation of attenuation with transmitted frequency

This process was repeated at several different frequencies ranging from 10MHz to 290MHz. The results of the tests are plotted in Figure 6-3. The levels of attenuation are below all the estimated levels (which average around 80dB as seen in Figure 2-1), but that is to be expected due to the non-ideal nature of practical engineering. Only the attenuation at 125MHz is much lower than expected, and it only deviates by a factor of approximately 1/2. In fact, in general the attenuation is higher than expected. Even the low point at 125MHz is a moderate amount of attenuation. Because of the generally good results and the amount of time available, it was reasoned that no more time or money should be spent on research-oriented tests to obtain higher accuracy results of the exact shielding properties at other frequencies.

The RF enclosure has a higher attenuation than expected while adding the expected amount of mass (and therefore radiation length); therefore, it passes the test and will keep the MVD isolated from RF noise well enough to keep the signal to noise ratio at an acceptable level. Therefore, the RF enclosure is an acceptable MVD subassembly.

6.2 Testing the Air and Humidity Tightness

After the RF shielding tests were completed, another set of tests were performed to determine if the enclosure could keep outside air from seeping into the MVD. In order to determine this, the reasoning was used that if air at a higher than atmospheric pressure inside the enclosure causes significant air flow out through a leak, then the enclosure is not air tight, and outside air will be able to flow into the enclosure if the pressure inside is atmospheric or less. This reasoning is not necessarily correct, because it is possible that a positive pressure difference could have a different effect on the positioning of the enclosure than a negative pressure difference. This could happen if, for instance, the outer Rohacell cover was thinner than 0.25". If that were the situation, then the leaks in the enclosure could be modeled as check valves, and the functional properties of the check valve would have to be determined in order to learn how to stop leaks. However, the experimental setup for a positive pressure test provided a very good return for the amount of effort and time used to set it up, so it was the model used.

Assuming that the reasoning used in designing the tests is suitable for the actual properties of the leaks in the enclosure, then the next step is to find a method to locate air leaks from a high pressure inside the enclosure. A commercially available leak detector fluid was found to work well enough for the tolerances we were looking for, i.e. leak flows greater than 0.002cfm. A fan was used to blow air through the enclosure and increase the pressure inside to 0.5inches of water. Then the leak detector fluid was used to locate any leaks. Some leaks were found, but the air flow out of the enclosure was negligible in most cases. In the non-negligible cases, the leaks were not due to problems with the RF enclosure, but rather with the temporary assembly of the MVD frame mock-up. Significant leaks occurred at the endplate shield/ D-rings interface and also at spots where the outer retaining rings were not held flush against the D-rings by the clamps. There were no significant leaks that were a result of a bad design, assembly, or installation of the RF enclosure; therefore, the enclosure passed the test and will keep the MVD sufficiently isolated from the temperature and humidity of the outside environment. Therefore, it is an acceptable MVD subassembly.

Section 7: Conclusions/ Recommendations

Many goals have been met during the course of this thesis project: 1) Work performed to determine the thermoforming, assembly, and installation procedures have shown that the RF enclosure's design is manufacturable; 2) Tests for air leakage and RF attenuation have adequately proved that it can isolate the MVD electronics from the outside environment's temperature, humidity, and RF noise while meeting the low mass and low percentage radiation length specifications; 3) The details of the fabrication and installation procedures have been published in two PHENIX technical documents, which will allow future RF enclosure workers to avoid errors that cost time and money; 4) Thermoforming, machining, and installation fixtures and tools have been designed, developed, and tested to make fabrication and installation of the RF enclosure easier and more time efficient; 5) Thermoforming test results will help decrease time and money spent on perfecting similar Rohacell thermoforming procedures in all applications.

More work should be performed in several areas before the projects can be considered completed: 1) The holding fixture that will keep the MVD secure while installing the inner and outer RF enclosures has not been designed; 2) The degree of loss of attenuation of the enclosure with the actual connectors and cables attached has not been determined; 3) The installation procedures for the RF enclosure have not been tested with the actual MVD frame; 4) The RF enclosure has not been tested in the PHENIX experimental hall environment or with the air cooling system of the MVD; 5) The fabrication procedures for the inner and outer retaining rings have not been specified; 6) The ability of the retaining rings to hold the inner and outer RF enclosures firmly in place has not been tested.

I recommend that the edge of the outer retaining ring in contact with the shielding foil be sanded or filed down to decrease the strain on the foil and thereby allow for a larger thickness growth in the outer Rohacell cover.

Section 8: Appendices

The appendices include an attenuation estimation calculation, three PHENIX technical documents, and the RF attenuation test data. The first appendix shows the equations and a spreadsheet that detail the calculation of the expected RF noise attenuation of the shield against a source that is 1m away from it. The second appendix describes the tests and results of the thermoforming properties of Rohacell IG-71 that were performed during the summers of 1996 and 1997. It can be found on the internet at http://p25ext.lanl.gov/phenix/mvd/notes/1998/1998notes.html and is numbered PHENIX-MVD-98-27, PHENIX Note 356. The third and fourth appendices provide a detailed description of the procedures chosen to fabricate the inner and outer, respectively, RF enclosures. They, too, are PHENIX documents and can be found on the internet at http://p25ext.lanl.gov/phenix/mvd/notes/1999/1999notes.html and are numbered PHENIX-MVD-99-1, PHENIX Note 370 and PHENIX-MVD-99-2, PHENIX Note 371, respectively. The fifth appendix is a spreadsheet detailing the data used in determining the RF attenuation properties of the prototype RF enclosure.

8.1 RF shield attenuation estimations based on three different noise source models

$$\text{E field reflection} = R_e = 322 + 10\log\left(\frac{G}{\mu d^2 f^3}\right)$$

$$\text{H field reflection} = R_m = 14.6 + 10\log\left(\frac{f d^2 G}{\mu}\right)$$

$$\text{Plane Wave reflection} = R_p = 168 + 10\log\left(\frac{G}{\mu f}\right)$$

$$\text{Absorption} = A = 131.5t\sqrt{fG\mu}$$

$$\text{Correction for multiple reflections} = C = 20\log(1 - e^{-2t/G})$$

SE[dB] = A[dB] + R[dB] + C[dB]

where:

- μ = relative permeability
- G = relative conductivity
- d = distance from source to shield [m]
- f = frequency [Hz]
- t = shield thickness [m]

From "Electrical Interference Handbook'

mu	G	d	f	t	delta
1	0.5	0.1	10000000	2.5e-05	2
		1	40000000		
		10	80000000		
		100	1.25e+08		
			2.9e+08		

(page 98) A	(page 260) R (E field)	(page 260) R (H field)	(page 260) R (plane wave)	(page 261) (neglect if A>10dB) B	SE (E field)	SE (H field)	SE (plane wave)	d	f
7	129	62	95	-20	116	49	82	0.1	10000000
15	111	68	89	-20	105	62	83	0.1	40000000
21	102	71	86	-20	102	71	86	0.1	80000000
26	96	73	84	-20	102	78	90	0.1	1.25e+08
40	85	76	80	-20	104	95	100	0.1	2.9e+08
7	109	82	95	-20	96	69	82	1	10000000
15	91	88	89	-20	85	82	83	1	40000000
21	82	91	86	-20	82	91	86	1	80000000
26	76	93	84	-20	82	98	90	1	1.25e+08
40	65	96	80	-20	84	115	100	1	2.9e+08
7	89	102	95	-20	76	89	82	10	10000000
15	71	108	89	-20	65	102	83	10	40000000
21	62	111	86	-20	62	111	86	10	80000000
26	56	113	84	-20	62	118	90	10	1.25e+08
40	45	116	80	-20	64	135	100	10	2.9e+08
7	69	122	95	-20	56	109	82	100	10000000
15	51	128	89	-20	45	122	83	100	40000000
21	42	131	86	-20	42	131	86	100	80000000
26	36	133	84	-20	42	138	90	100	1.25e+08
40	25	136	80	-20	44	155	100	100	2.9e+08

Frequency (MHz)	Plane Wave Model (dB)	(distance from source=1m) Electric Field Model (dB)	(distance from source=1m) Magnetic Field Model (dB)
10	82	96	69
40	83	85	82
80	86	82	91
125	90	82	98
290	100	84	115

8.2 Thermoforming Rohacell for the MVD's Radio Frequency Enclosure: PHENIX-MVD-98-27, PHENIX Note 356

Thermoforming Rohacell for the MVD's Radio Frequency Enclosure

Richard Conway
Massachusetts Institute of Technology
June 22, 1998

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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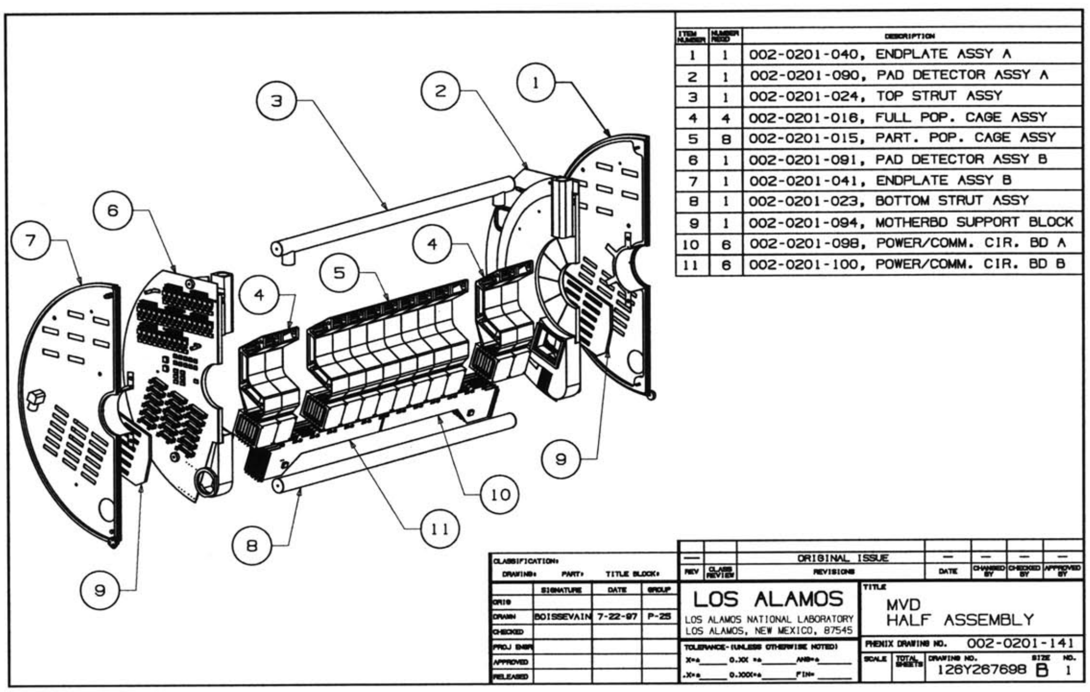


Figure 1: Exploded isometric view of the assembled RF Enclosure

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 Dielectric 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 physics 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 180°C ($T_{A1}=T_{A2}=180$°C). 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 105°C $< T_{F1} <$ 180°C.
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 23°C < T_{F2} < 68°C.

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 Zetex Plus 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.

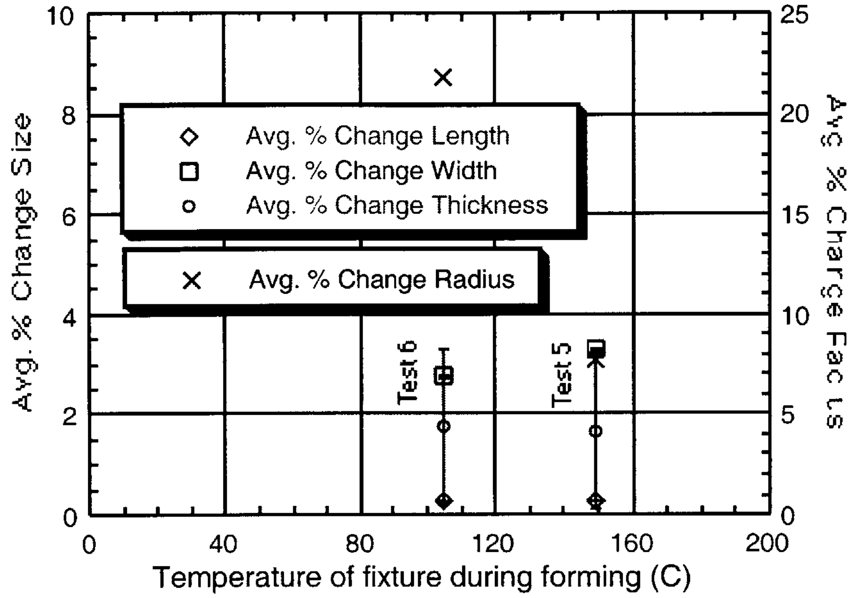
Eight tests were performed to help determine the optimal forming procedure for the inner enclosure. During three of the tests the jig temperature was not measured, so only five tests had data that could be compared while being certain that only one variable was changing during the comparison.

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.

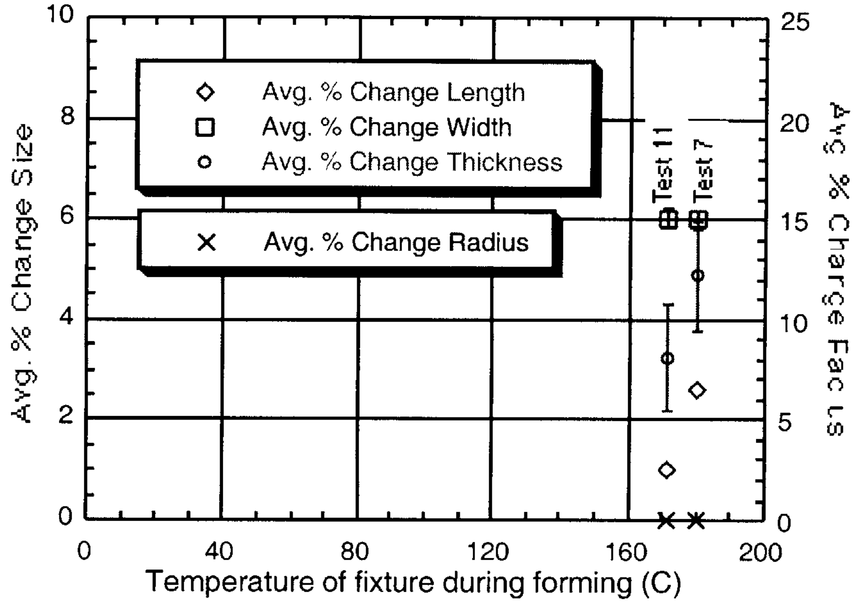
Graph 1:
3mm Tests 5 & 6



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).

Graph 2:
3mm Tests 7 & 11



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.

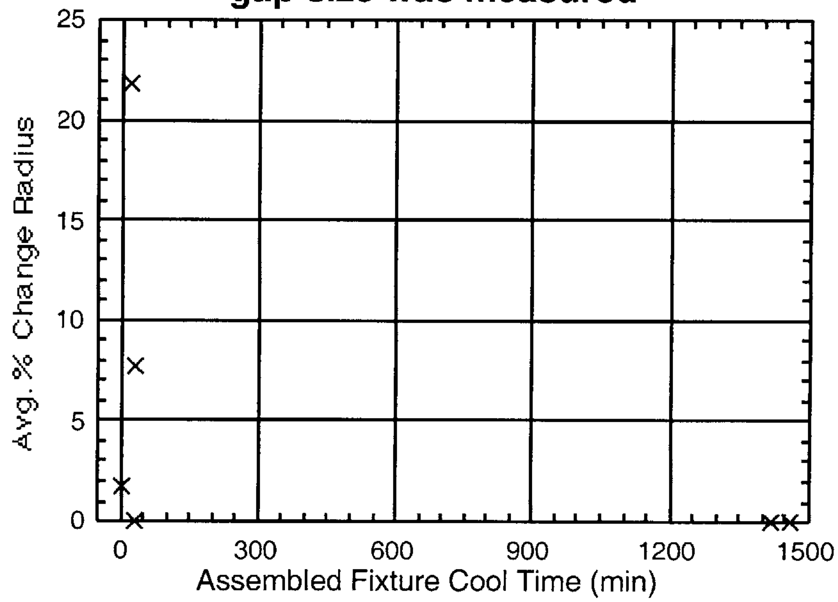
There is a sensible physical explanation as to why less springback occurs with a slower cool down rate. I propose that a major cause of springback could be residual stresses putting the expanding side of the Rohacell (the side farthest away from the center of curvature) in tension. Because the expanding 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.

Graph 3:
All 3mm tests in which gap size was measured



- 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.

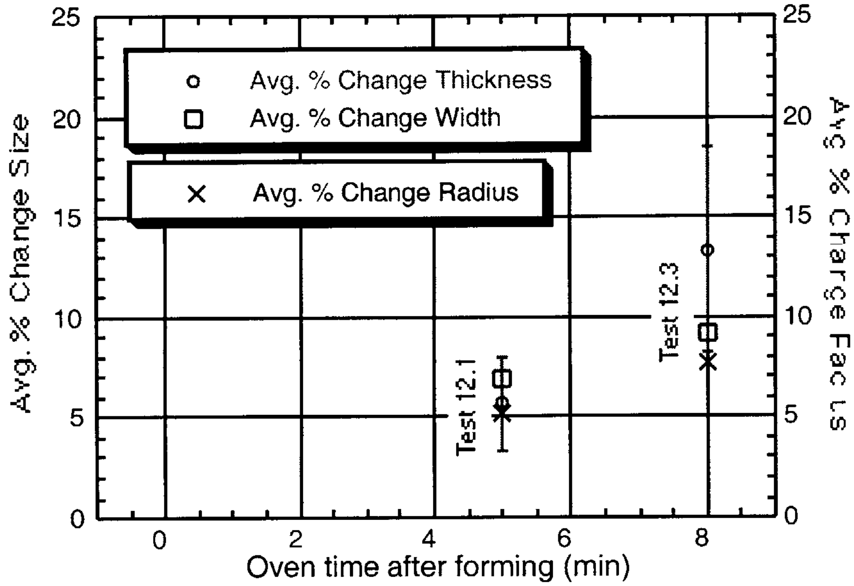
Because of changes in the forming procedure from test to test, all the data is not graphed together. Only graphs from some of the data are shown. However, all the data can be found in Appendix F.

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}) = 5min
- Amount of time the Rohacell was allowed to cool down in the fixture (t_{f4}) = 0min

Graph 4:
0.25" Tests 12.1 and 12.3



Observations of Graph 4

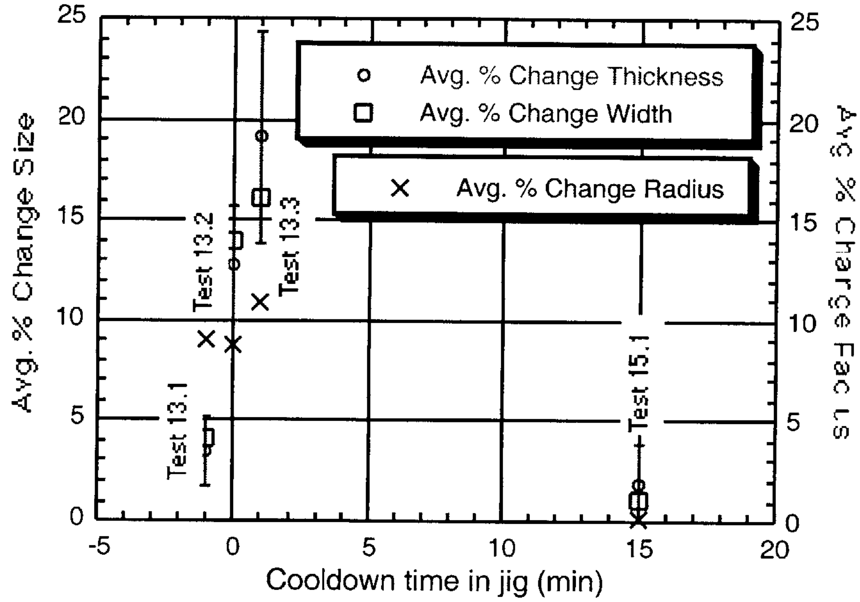
- Graph 4 suggests that Rohacell's percent growth is higher the longer it is left in the oven after it has been formed.
- Also, the percent change in radius does not change significantly in the graph, and so Graph 4 suggests that percent change of radius is independent of the time it is allowed to stay 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}) = 3min
- Amount of time the Rohacell was in the oven after being formed (t_{f3}) = 0min

Graph 5:
0.25" Tests 13.1, 13.2, 13.3, and 15.1



(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 Cdr Graph 6

  165 C - 173 Cdr Graph 7
- Amount of time the Rohacell was in the oven after being formed (t_{f3}) =

3 minutes for Graph 6

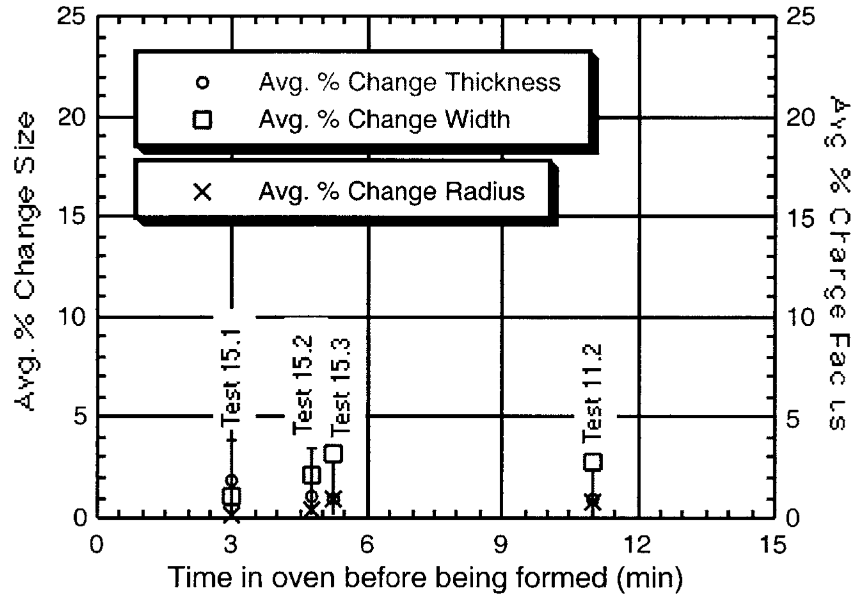
2 - 3 minutes for Graph 7

- 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

Graph 6:
0.25" Tests 11.2, 15.1, 15.2, and 15.3

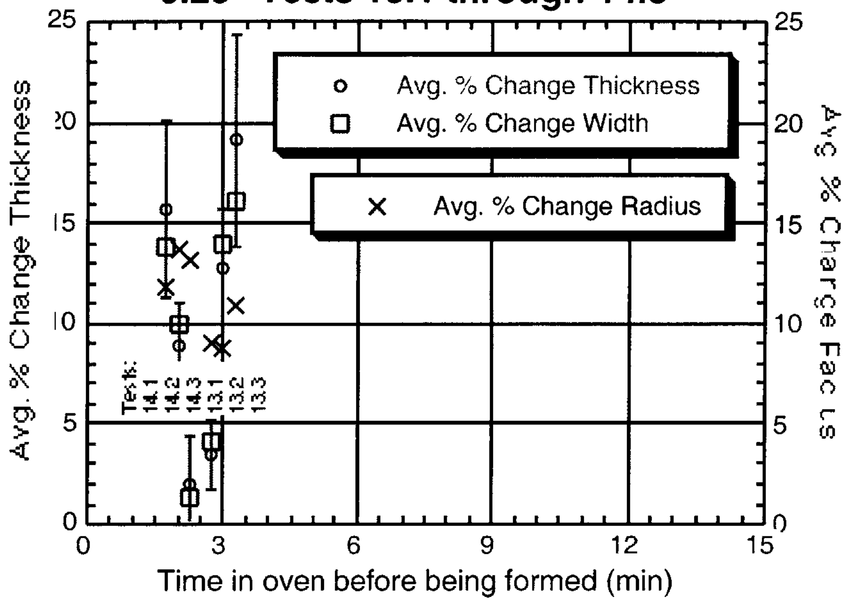


Observations of Graph 6

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.

Graph 7:
0.25" Tests 13.1 through 14.3



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

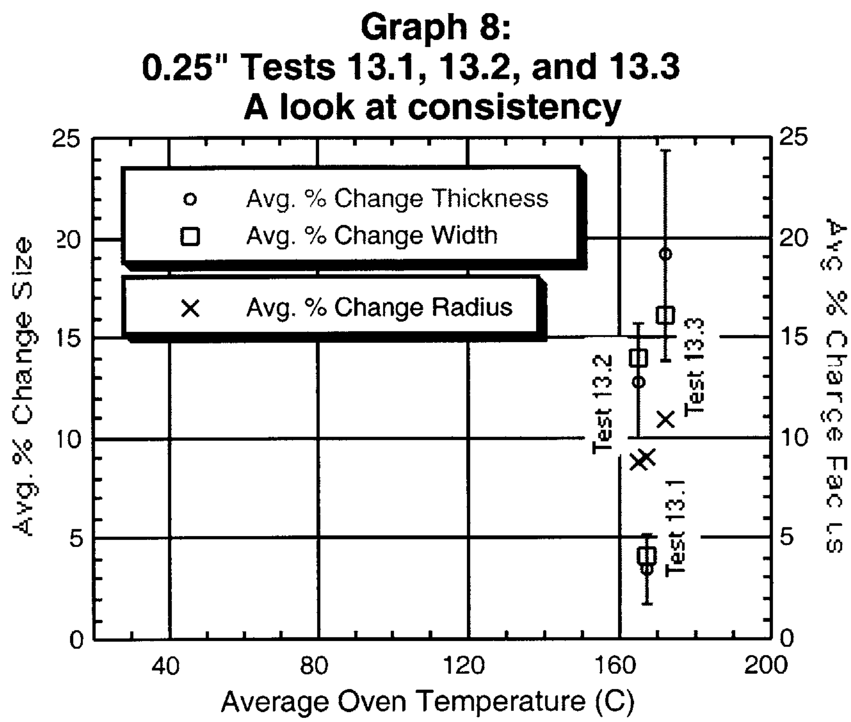
- Amount of time the Rohacell was in the oven after being formed (t_{f3}) =
  0 minutes for Graph 8
  0 minutes for Graph 9
  0 minutes for Graph 10

- Amount of time the Rohacell was allowed to cool down in the fixture (tf4) =

  0 minutes for Graph 8

  0 minutes for Graph 9

  15 minutes for Graph 10

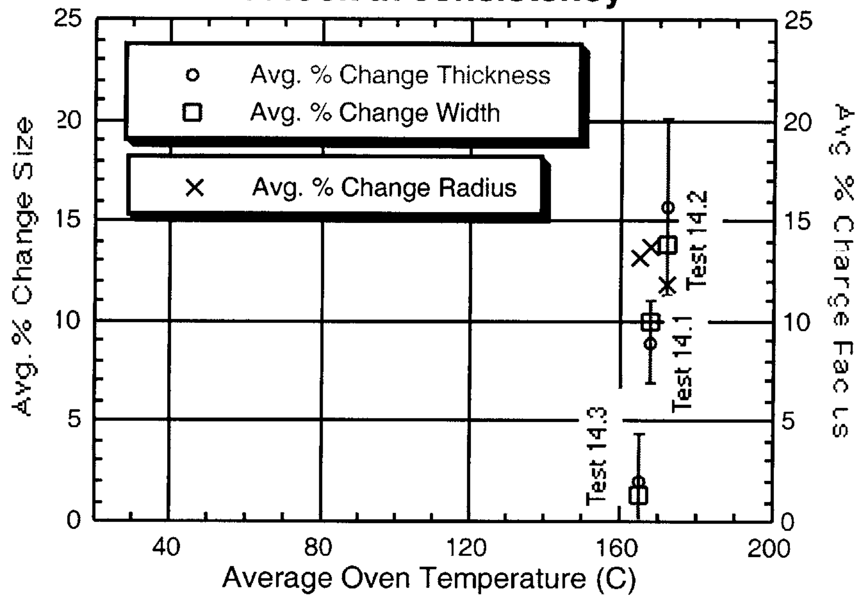


Observations of Graph 8

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.

Graph 9: 0.25" Tests 14.1, 14.2, and 14.3 A look at consistency

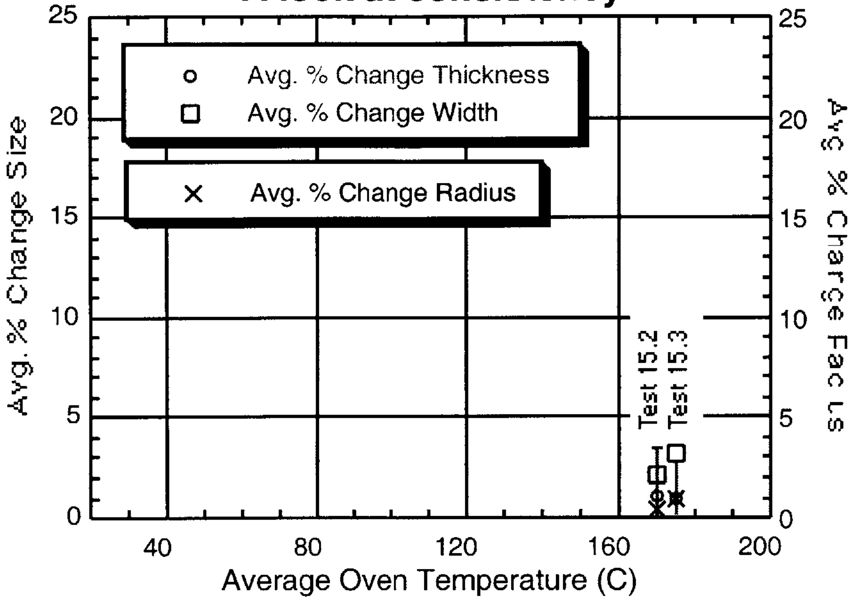


Observations of Graph 9

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.

Graph 10:
0.25" Tests 15.2 and 15.3
A look at consistency



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. 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)

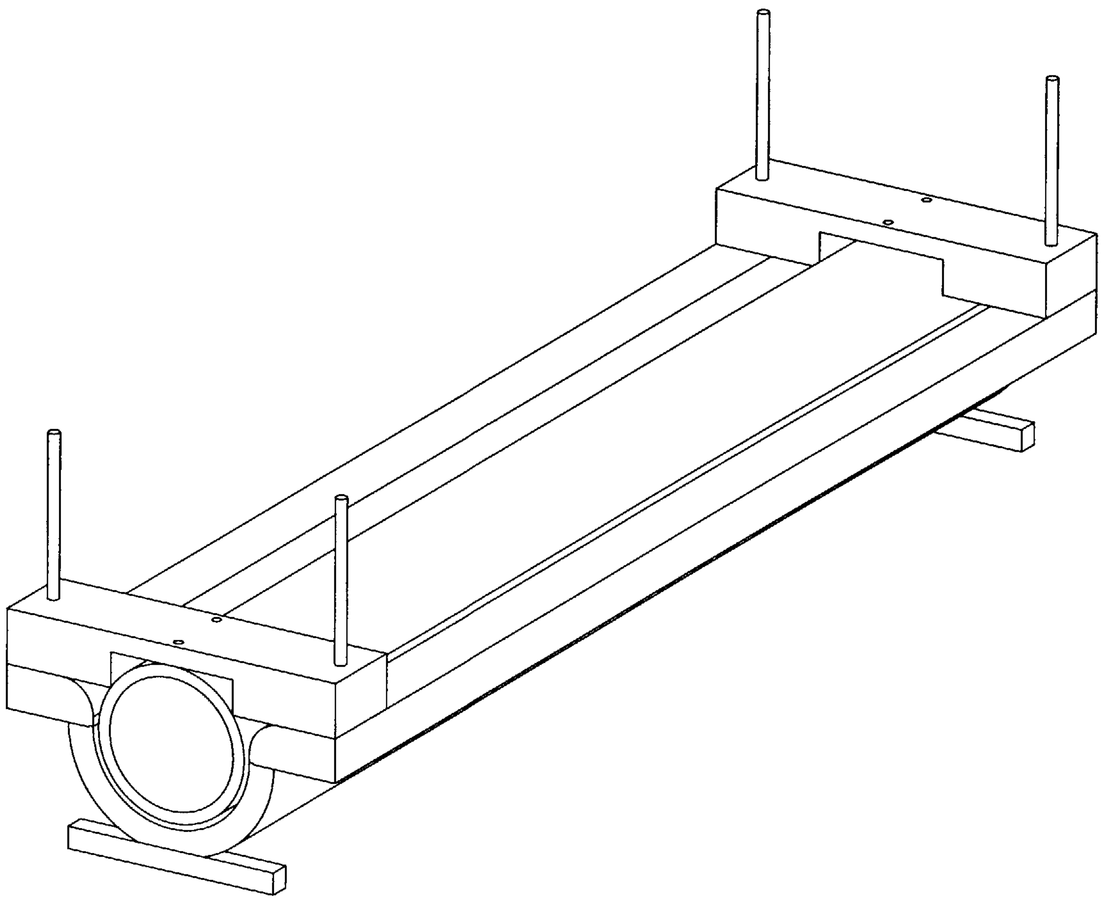
2) **The pressure of the fixture on the Rohacell during the cool down process helps to reduce the size growth** (supported by comparison of graphs 6 & 7 and by comparison of graphs 8, 9, & 10)

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.



APPENDIX B

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).

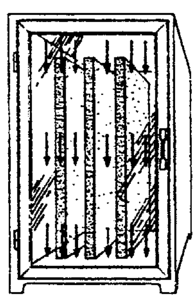
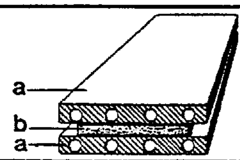
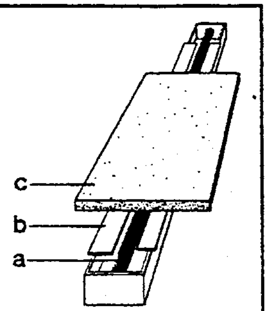


Fig. 37: Heating in a cabinet with air circulation



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

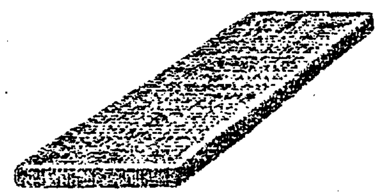


Fig. 40: ROHACELL sheet covered all around

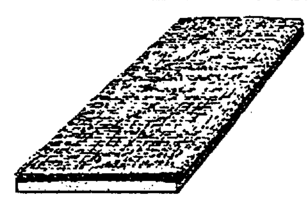


Fig. 41: ROHACELL sheet covered on one side only

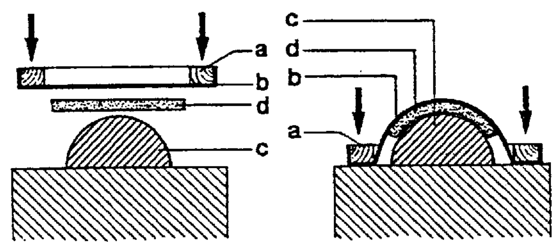
For series production, the heating plates and the forming tool can be put in such a position that, when the heated ROHACELL blank is quickly and automatically taken from the heating plates to the forming tool, there is often no need for any cover.

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.

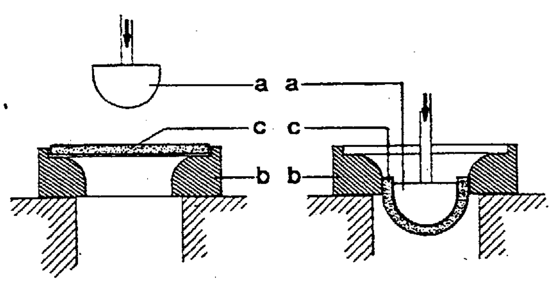
The foam plastic cools quickly because of its low heat capacity, and once the formed part has cooled down to c. 176 °F (80 °C) it may be removed from the tool. With simple parts, the molds are not subjected to a substantial amount of heat, so that hardwood molds are adequate. Polyester and epoxy resin 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.



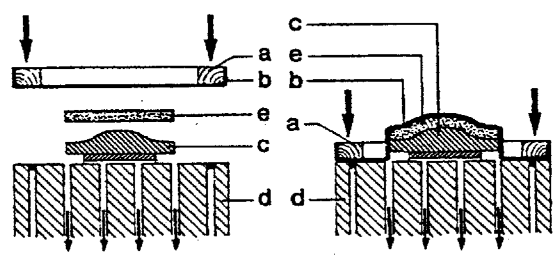
a) frame b) stretch rubber c) mold d) ROHACELL

Fig. 44: Forming ROHACELL with stretch rubber



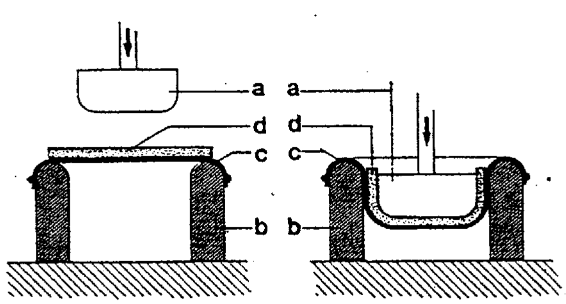
a) force plug b) annular mold c) ROHACELL

Fig. 42: Forming of a hemisphere from ROHACELL



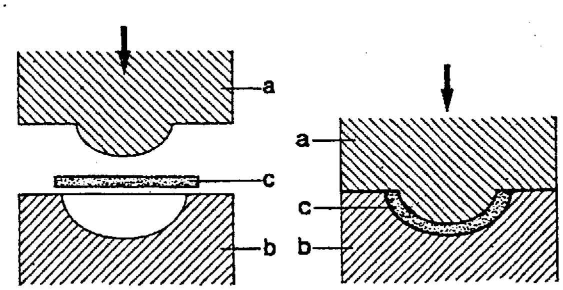
a) frame b) stretch rubber c) mold
d) vacuum table e) ROHACELL

Fig. 45: Forming ROHACELL with stretch rubber



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

:LL with stretch rubber



a) force plug b) mold c) ROHACELL

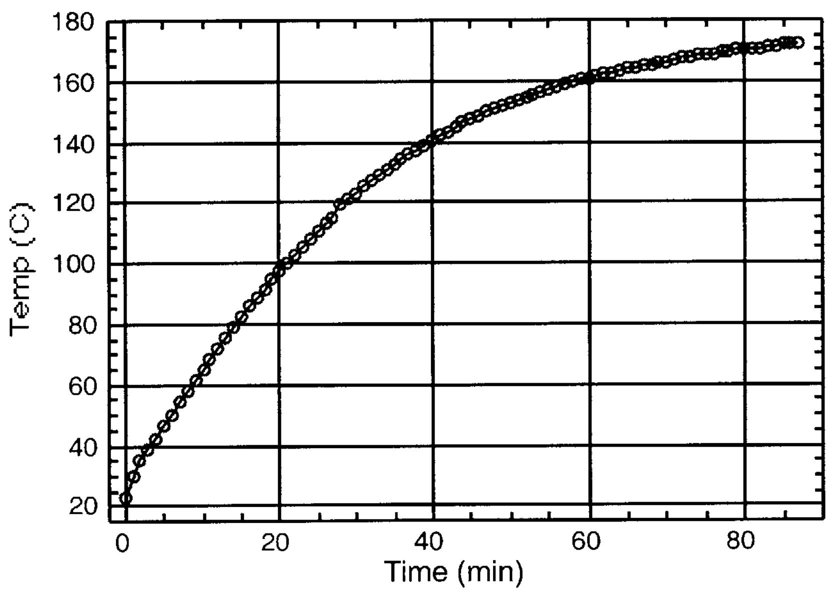
Fig. 46: Forming in the tool

APPENDIX C

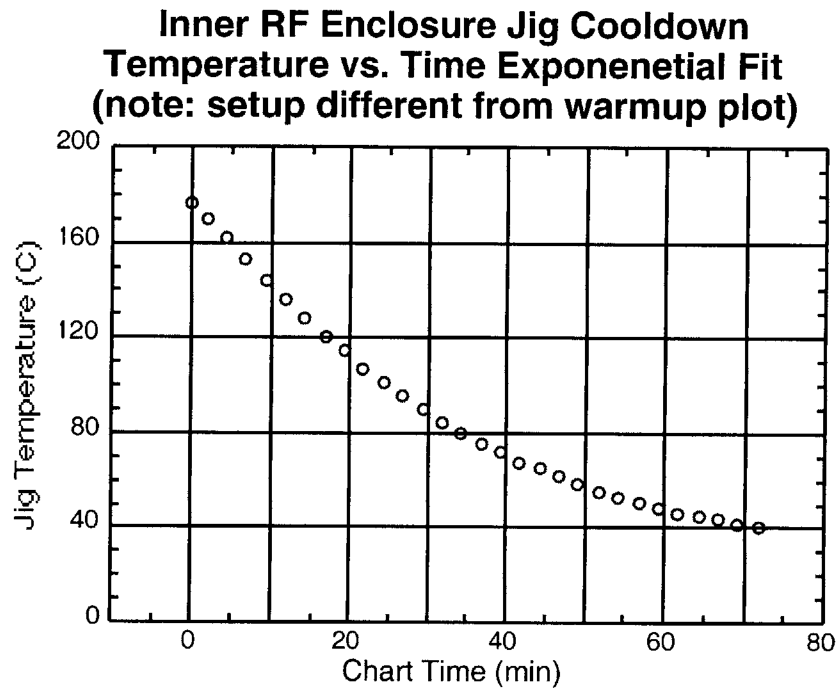
Using a type "J" thermocouple and a rapid sampling voltmeter, the rate at which the jig warms up and cools down was determined. The two halves of the jig are warmed with the jig unassembled, but during the cool down process the jig remains assembled with the formed sheet still inside. The formed sheet 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

Inner RF Enclosure Aluminum Jig
Warmup Time vs. Temp for Oven at 180 C
(note: setup different for cooldown test)



APPENDIX C2



y=23+161.57*exp(-x/32.3426) R^2=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-05
	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-05
	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-05
	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-05
	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-05
	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-05
Unc. % Change Length (95%)		0.0117517	0.0099683	0.00994721	0.009976722	0.00993455	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	-0.0047380 4	-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 Calculation

Caliper Measurement Error Analysis

THICKNESS Error Analysis				WIDTH Error Analysis			
Same spot meas.	Left/right of line	Up&down the line		Same spot meas.	Left/right of line	Up&down the caliper jaws	
Formed	Formed	Formed	Flat(diff. piece)	Formed	Formed	Formed	Flat(diff. piece)
0.284	0.284	0.298	0.258	2.284	2.282	2.282	1.639
0.283	0.286	0.287	0.258	2.283	2.284	2.281	1.64
0.283	0.283	0.292	0.257	2.283	2.283	2.28	1.641
0.284	0.284	0.289	0.257	2.283	2.282	2.28	1.639
0.283	0.285	0.292	0.258	2.282	2.28	2.271	1.638
0.283	0.283	0.288	0.258	2.281	2.283	2.279	1.633
0.282	0.285	0.313	0.258	2.283	2.282	2.28	1.637
0.283	0.283	0.297	0.257	2.282	2.283	2.28	1.637
0.283	0.282	0.29	0.257	2.282	2.281	2.28	1.637
0.282	0.283	0.286	0.257	2.282	2.281	2.279	1.638
0.282	0.283	0.283	0.258	2.282	2.282	2.279	1.638
0.282	0.285	0.294	0.258	2.283	2.282	2.278	1.633
0.282	0.281	0.314	0.258	2.281	2.282	2.278	1.635
0.284	0.283	0.292	0.257	2.281	2.282	2.279	1.635
0.282	0.283	0.288	0.258	2.28	2.282	2.268	1.635
Avg.	Avg.	Avg.	Avg.	Avg.	Avg.	Avg.	Avg.
0.2828	0.283533333	0.29353	0.2576	2.282133333	2.282066667	2.27826667	1.637
S.D.	S.D.	S.D.	S.D.	S.D.	S.D.	S.D.	S.D.
0.000774597	0.001302013	0.00903	0.000507093	0.001060099	0.00096115	0.00375056	0.00239045

Bias Unc. (flat-95%)	Bias Unc. (formed-95%)	Bias Unc. (flat-95%)	Bias Unc. (formed-95%)
0.001597617	0.00916	0.00278602	0.00401426

Appendix F: Other 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 DEV	Bias Unc. (95%)	u(thick-95%)	INITIAL WIDTH	FINAL WIDTH	% WIDTH	AVG % WIDTH	STANDARD DEV	Bias Unc. (95%)	u(width-95%)	GAP	Cooling Pres. (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 time 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 let cool in emmebled jig, then let cool ir half jig
	2	0.256	0.256	0.00%					2.005	2.075	3.49%							.	.			.	.	
	3	0.256	0.259	1.17%	0.91%	0.82%	1.26%	1.50%	2.005	2.058	2.54%	2.61%	0.78%	0.11%	0.76%	0.086	17,913	.	.			.	.	
	4	0.255	0.259	1.57%					2.008	2.077	3.44%							.	.			.	.	
	5	0.255	0.254	-0.39% X					2.003	2.062	2.95%							.	.			.	.	
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%	1.998	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	17,366	.	.			.	.	.
	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%	1.86%	1.26%	2.33%	1.998	2.283	14.38%	13.89%	1.80%	0.11%	1.81%	0.375	17,366	.	.			.	.	.
	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	165	165	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%	3.00%	1.27%	5.16%	2.001	2.155	7.70%	9.20%	0.98%	0.11%	0.98%	0.33	17,366	.	.			.	.	.
	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%	1.82%	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%	2.55%	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	17,366	.	.			.	.	.
	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%					1.998	2.043	2.31%							.	.			.	.	.
	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 let cool in ammebled jig, then let cool ir half jig
	2	0.258	0.261	1.16%					1.997	2.064	3.36%							.	.			.	.	
	3	0.257	0.262	1.95%	0.97%	1.21%	1.45%	1.88%	1.993	2.063	3.51%	3.19%	0.26%	0.11%	0.30%	0.094	17,830	.	.			.	.	
	4	0.257	0.261	1.56%					1.995	2.06	3.26%							.	.			.	.	
	5	0.258	0.262	2.34% X					1.994	2.05	2.81%							.	.			.	.	

8.3 Fabricating, Assembling, and Installing The Inner Radio Frequency Enclosure Of the Multiplicity Vertex Detector: PHENIX-MVD-99-2, PHENIX Note 371

Fabricating, Assembling, and Installing the Inner Radio Frequency Enclosure of the Multiplicity Vertex Detector

Richard Conway

September 18, 1998

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Part I. Fabricating the inner Rohacell cover

Rohacell is a closed-cell polymethacrylimide rigid foam. It has a high strength to density ratio, which makes it very suitable for the conditions and constraints of the MVD. The main structural component of the inner RF Enclosure is a 3mm thick half-cylinder of Rohacell that acts as a support for the RF shielding and as a barrier between the MVD's silicon strip detectors and the beryllium beam pipe. The half-cylinder can be made cheaply with minimum material waste by thermoforming. The thermoforming process heats a Rohacell sheet to the temperature at which the chemical bonds that hold it together weaken so much that the sheet can be reshaped without fracturing it. When thermoforming Rohacell, one must be careful to observe time, temperature, and humidity variations because the Rohacell has a tendency to return towards its pre-thermoformed shape (springback) as well as to grow in size. Therefore, the procedure below should be followed precisely in order to minimize the springback and thickness growth, and thereby meet the tight tolerances of the design.

Part I, A.

The Materials Needed to Fabricate the Inner Rohacell Cover

- one 3mm thick sheet of Rohacell IG-71 measuring at least 30"x7.25"
- a ruler, meter stick, or tape measure (preferably a T-square)
- a marker
- a razor blade or X-acto knife
- the inner enclosure forming jig
- an air-circulating oven large enough to easily fit the inner enclosure forming jig (preferably the VWR 1655D oven in TA-53-1-C114)
- a watch or timer
- heat resistant gloves (preferably ones with fingers that are not clumsy)
- a plastic bag big enough to hold the 30"x7.25" Rohacell sheet
- four (4) C-clamps with a jaw space of at least 2.5"

Part I, B.

The Procedure for Fabricating the Inner Rohacell Cover for the MVD

Note: Always use heat resistant gloves when operating the oven.

1) Measure and cut the 3mm sheet of Rohacell to 30"x7.25".
2) Preheat the oven to 120˚C.
3) Put the sheet of Rohacell in the oven for at least 2 hours to dry it out.
4) Take the dried Rohacell out of the oven and store it in a dry environment (a plastic bag will suffice).
5) Preheat oven and forming fixture to 185˚C (If you are using the VWR 1655D oven, then set the oven temperature to 200˚C, wait for the oven to warm up, put the room-temperature fixture in the oven, and in approximately 70 minutes it will have reached 185˚C).
6) Set the oven temperature to 185˚C.
7) With the fixture still in the oven, heat the dried sheet of Rohacell to 185˚C (with the VWR 1655D oven at 185˚C , it takes approximately 6 minutes for 3mm thick Rohacell to come up to the forming temperature from room temperature). When at the correct temperature, the Rohacell should be very pliable.
8) While still in the oven, quickly put the heated Rohacell onto the bottom half of the forming fixture (the Rohacell will cool to below the forming temperature in a matter of just a few seconds).
9) Form the Rohacell by assembling the forming fixture halves quickly and smoothly. When you push the top half of the fixture onto the Rohacell and into the bottom half, the Rohacell should form into a half-cylinder. Try to keep the Rohacell as centered as possible on the bottom half so that one side of the half-cylinder does not form longer than the other.
10) With everything still in the oven, clamp the fixture halves together with C-clamps at the four corners to minimize the thickness growth.
11) Allow the formed Rohacell to cool slowly to below 35˚C before removing it

from the fixture. It is easiest to just keep the clamped fixture in the oven with it turned off.

12) Using the forming fixture to hold the Rohacell in place, an X-acto knife, and a measuring tape, cut the formed specimen to the final length and arc length (width) of 29.06"x5.56". When completely disassembled, the bottom half of the forming fixture can be used as a template to cut the Rohacell to the correct arc length, and putting the whole cylinder and half cylinder of the fixture together provides a way to make the length cut square with the axis.

13) Check radius and thickness values to ensure the enclosure meets tolerances using this formula:

$$(\%\ \text{Springback}) / 100 * 46.5\ \text{mm} + (\%\ \text{Thickness Growth}) / 200 * 3\text{mm} < 1.68\ \text{mm}$$

The springback can be measured by dividing the Rohacell's change in outer radius by the inner radius of the bottom half of the forming fixture. The thickness growth can be measured by dividing the change in the Rohacell's thickness from before thermoforming to after by its before thickness.

Part II. Assembling the inner RF enclosure

The inner RF enclosure has four main parts: 1) the Rohacell cover, 2 & 3) two laminates of aluminum foil adhered to mylar (a polyester sheet material), and 4) a lone layer of mylar which provides a barrier between the Rohacell and the silicon strip detectors. In the laminates, the aluminum foil acts as the RF shielding, and the mylar acts as an insulator between the two layers of aluminum foil as well as to help the foil resist tearing. The assembly procedure consists of: 1) assembling the laminates, 2) adhering the laminates to each other and to the surface of the Rohacell cover with the smaller radius, and 3) adhering the lone mylar sheet to the other side of the Rohacell cover.

In order to access a completely assembled half of the MVD, the inner RF enclosure must be removed and cannot be reused. Therefore, several inner enclosures should be assembled to ensure that there are enough replacements. Once an inner enclosure is assembled it should be stored in an environmental chamber at the Phenix Hall until needed for installation, so that the uncovered hygroscopic Rohacell ends do not expand after being installed.

Part II, A.

The Materials Needed for Assembling the Inner Radio Frequency Enclosure

- two (2) sheets of 0.5mil thick Mylar measuring at least 30"x35"
- one (1) sheet of 0.5mil thick Mylar measuring at least 7"x29"
- two (2) sheets of 0.5mil thick aluminum foil measuring at least 30"x35"
- two (2) sheets of Dielectric Polymers NT 988-2 dry transfer adhesive at least 30"x35"
- two (2) sheets of Dielectric Polymers NT 988-2 dry transfer adhesive at least 6"x29"
- one (1) sheet of Dielectric Polymers NT 988-2 dry transfer adhesive at least 7"x29"

- large template (28.5"x33") for marking cutting pattern
- small template (7"x29") for marking cutting pattern
- tape (doesn't matter what kind)
- a cardboard sheet measuring approximately 48" square
- a measuring tape or meter stick
- a marker
- a razor blade or X-acto knife
- a manufactured Rohacell inner cover
- a "rolling bar" at least 35" long

Part II, B.

The Procedure for Assembling the Inner Radio Frequency Enclosure for the MVD

Note: If at any time the foil tears in any place that will be on the MVD after the installation is complete, then that foil should be replaced with another. Because the frequencies of the RF radiation in Phenix Hall are not known, it is better to assume that there will be high frequencies that could pass through any small cracks or tears.

1) Cut out a sheet of 0.5mil thick mylar to approximately 30" x 35" using a pair of scissors.
2) Cut out a sheet of 0.5mil thick aluminum foil to approximately the same dimensions with the scissors.
3) Stretch taut and tape down the foil's corners and middles of edges onto a large, flat sheet of cardboard.
4) Cut out a sheet of Dielectric Polymers NT 988-2 dry transfer adhesive to approximately the same dimensions using a sharp razor blade.
5) Match up and adhere one corner of the dry adhesive to the foil and smooth out the rest of the adhesive starting at that corner while minimizing wrinkles and overlap, making sure that the adhesive is adhered only to the foil.
6) Run your fingertip along the edges of the adhesive backing to ensure that the

adhesive does not pull up when removing its backing.

7) Slowly pull off the backing while keeping it parallel to the cardboard surface to minimize stretching of the foil.
8) Restretch and retape the foil if pulling off the adhesive backing caused the aluminum foil to become loose on the cardboard.
9) Match up and lay down one corner of the mylar sheet on the foil/ adhesive laminate and spread it out evenly over the adhesive while minimizing wrinkles and overlap, making sure to cover all exposed dry adhesive.
10) Make sure that the mylar is firmly adhered to the foil providing a very flat foil/ adhesive/ mylar laminate, and "pop" any large air bubbles between the mylar and adhesive with a needle.
11) Use a felt tip marker to mark the outline of the large template on the laminate.
12) Remove the template, and use a razor blade to cut out the laminate along the marker lines. Slightly round (1/8" radius) the corners of the inner cut out portions in the middle to prevent the laminate from easily tearing.
13) Repeat steps 1 through 12 to make another laminate.
14) Stretch out and lightly tape down one of the cut out laminates with the FOIL SIDE UP.
15) At both ends of the laminate lightly tape down a sheet of paper at the cut-out section, aligning the center of the paper's edge with the center of the longer edge of the cut-out section.
16) Cut out another sheet of adhesive 6" x ~33".
17) Match up the adhesive with the cut out portion of the middle of the laminate, and lay it down starting at one corner and smoothing out from that corner. The adhesive should overlap onto the paper.
18) Run your fingertip along the edges of the backing to ensure a good stick.
19) Peel off the adhesive backing starting at one corner and keeping the backing parallel to the cardboard to minimize stretching of the laminate.
20) Untape and remove the papers with the extra adhesive on them.
21) Lay the other laminate, MYLAR SIDE DOWN, onto the laminate with the

adhesive on it. Make sure to match up the middle cut out sections precisely.

22) Repeat steps 15 through 20 to lay down another layer of adhesive on top of the two laminates.
23) Untape the bottom laminate from the cardboard without tearing it.
24) Set up the laminates so that the middle section with the adhesive on it can be rolled onto the smaller radius side of the Rohacell inner cover with the "rolling bar". This means that the edge of the adhesive needs to be lined up precisely with the edge of the Rohacell (sticky side down and touching inside corner of smaller radius of Rohacell), and the rolling bar needs to be placed on the opposite side of the adhesive so that as the bar is rolled towards the Rohacell, the laminates are adhered to the Rohacell at their middle sections.
25) Slowly roll the laminates onto the Rohacell, and minimize the wrinkling by keeping the laminates taut at the edges.
26) Firmly smooth out any wrinkles that occurred during the adhesion. This is easiest and most safely done by putting the Rohacell and laminates into the bottom half of the forming fixture, so that more pressure can be used to smooth, yet there is less chance of breaking the Rohacell.
27) Stretch out and tape down the corners and edges of the 10" x 35" piece of mylar to the cardboard.
28) Cut out a sheet of adhesive 9" x 34".
29) Lay down the adhesive on the center of the mylar.
30) Use the 7" x 29" template to mark out the cutting lines on the mylar/ adhesive/ backing laminate.
31) Remove the template and cut along the lines.
32) Mark the middles of the shorter edges of the mylar with a marker.
33) Mark the middles of the shorter, curved edges of the Rohacell inner cover.
34) Roll the laminates attached to the Rohacell inner cover up and push them into the "trough" of the Rohacell.
35) Lay the laminate down flat with the adhesive side up, and use double-sided tape underneath the laminate to tape ONE of the long edges of the mylar to the surface.

36) Align the marks for the middle of the shorter edges of the laminate with the marks for the middle of the shorter edges of the Rohacell.

37) Adhere the middle edges, and then roll the Rohacell towards the long edge that is taped down, making sure to keep it taut to minimize wrinkling. The laminate will go past the Rohacell, but should not be adhered to anything yet.

38) Untape the mylar from the surface and tape down the other long edge of the laminate. Then repeat the rolling process to adhere the laminate to the Rohacell.

39) Untape the mylar from the surface, and unroll the foil laminates from the "trough" of the Rohacell.

40) Put the Rohacell down on the surface so that a "tunnel" is formed, flatten out the foil laminates on the surface, and then adhere the extra part of the mylar laminate to the foil laminate. Make sure that there is no gap between the edge of the Rohacell and the adhesion between the foil and mylar laminates.

41) Press on the mylar laminate to ensure good adhesion to the Rohacell (most safely done by placing the assembly on the top half of the forming fixture so larger pressure can be applied without fear of cracking the Rohacell).

Part III. Installing the inner RF enclosure into the MVD

An inner enclosure will need to be installed every time the barrel electronics of the MVD are accessed, because the old inner enclosure will be destroyed when it is removed from its O-ring grooves. The installation consists of two main parts: 1) aligning, adhering, and clamping the Rohacell section to the endplates, and 2) locking the laminates into the O-ring grooves to make an air-tight and RF radiation-tight enclosure.

Part III, A.

The Prerequisites for Installation of the Inner RF Enclosure into the MVD

The inner radio frequency enclosure should be one of the last components installed because it will seal off one side of an MVD-half completely. The outer RF enclosure should be installed prior to the inner because it provides a portion of the O-ring grooves that the inner enclosure must be installed into. The installation procedure must be both safe and reliable, because all of the MVD electronics will be in place during the inner enclosure's installation, and any bumps or jerks could cause some of the more delicate electronics to fail.

Part III, B.

The Materials Needed for Installing the Inner RF Enclosure into the MVD

- a ~40" x ~40" sheet of tacky mat material
- two ~5" O.D. half cylinders (from the bottom halves of the old and new forming fixtures)
- Two (2) inner retaining rings
- Six (6) 0.25" long, 4-40 UNC flathead screws
- Four (4) 27" long strips of 0.07 urethane O-ring material

- Eight (8) 10" long strips of 0.07 urethane O-ring material
- a flathead screwdriver
- a modified spline tool
- 1" wide double-sided tape
- an MVD half held inside the Maintenance Test Stand

Part III, C.

The Procedure for Installing the Inner Radio Frequency Enclosure for the MVD

1) Apply one 1" x 6" strip of double-sided tape to each of the aluminum cuffs at the edges closest to the endplates, making sure to cover the entire half circumferences of the cuffs. Cut off any excess tape. (Installation will occur while the MVD half is held securely in place by the Maintenance Test Stand.)
2) Put small pieces of putty adhesive onto the corners of the inner (smaller) D-ring where the Rohacell section stops and the O-ring grooves start.
3) Loosely roll the laminate flaps into the "trough" of the Rohacell section of the assembled inner RF enclosure to get them out of the way for the next step.
4) Adhere the Rohacell section to the double-sided tape and putty, making sure that the edges of the Rohacell extend symmetrically to the flat edges of the D-rings where the O-ring grooves start.
5) Unroll the bottom laminate for the side closest to you from the Rohacell "trough" and pull it taut over the O-ring grooves on the side of the MVD closest to you.
6) Use the sharper disc of the spline tool to push the laminate into the O-ring groove of the longer <u>inner</u> seal strip of the outer enclosure. Make several light passes instead of one heavy pass so that the ripping of the foil is minimized.
7) Near one end of the seal strip, take one of the longer urethane O-rings and push it into the crease in the laminate made by the spline tool. Use one hand to make sure that the O-ring does not slip in the groove and that the MVD

does not rock or tilt, and use your other hand to use the spline tool disc with the groove in its edge to push the O-ring all the way into the groove. You will have to stretch the O-ring material a little to get it to fit into the groove.

8) Repeat steps 6 through 7 twice using the shorter O-rings for the two shorter O-ring grooves in the D-rings.

9) Cut the extra laminate from around the O-ring grooves by running a razor blade along the laminate in between the inner and outer grooves.

10) Repeat steps 5 through 9 on the unsealed side of the MVD half.

11) Repeat steps 5 through 10 for the top laminate layer, but alternately cut the extra laminate off by running the razor blade along the outer edges of the D-rings and seal strips.

12) Screw in the inner retaining rings with the six flat head screws. Check to make sure that they do not allow the Rohacell to move in the cuff and are not cutting into the laminates.

8.4 Fabricating, Assembling, and Installing The Outer Radio Frequency Enclosure of The Multiplicity Vertex Detector: PHENIX-MVD-99-1, PHENIX Note 370

Fabricating, Assembling, and Installing the Outer Radio Frequency Enclosure of the Multiplicity Vertex Detector

Richard Conway

January 5, 1999

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I. Overview of the Outer RF Enclosure

The MVD's Radio Frequency Enclosure has three main parts: the inner enclosure, the outer enclosure, and the side panels (see Figure 1 below). The outer enclosure functions as an RF shield to help insure the required 10:1 signal-to-noise ratio is met as well as a barrier to external temperature and water vapor to ensure that the environment inside the MVD can be maintained. The two 0.5mil thick aluminum foil layers provide both the approximately 8dB of RF noise attenuation at 10MHz as well as an air-tight and water-tight seal. Rohacell IG-71 foam, thermoformed to the correct hemi-cylindrical dimensions, serves as the structural support for the aluminum foil RF shield, which is adhered to both large surfaces of the Rohacell by Dielectric Polymer's NT 988-2 dry transfer adhesive. Two aluminum O-ring seal strips make the electrical connections from the aluminum foil to the inner RF enclosure. They are cemented into a small groove in each of the long edges of the Rohacell through a conductive epoxy. The whole assembly is held in place by two aluminum retaining rings that run along the curved outer edges of the MVD's D-rings and by four earthen O-rings that keep the inner enclosure locked into the seal strips.

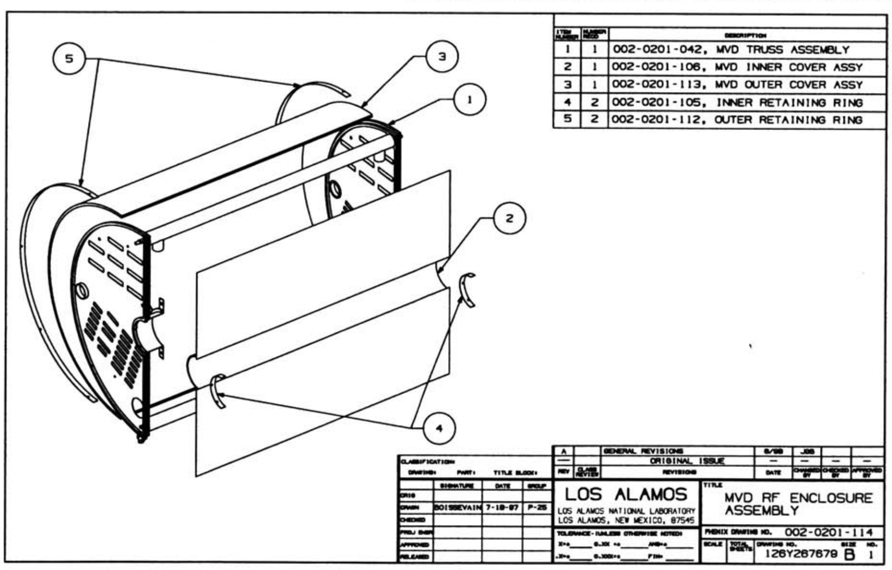


Figure 1: The MVD's Radio Frequency Enclosure
(Detail 1 is the Truss Assembly, detail 2 is the Inner Enclosure, and detail 3 is the Outer Enclosure)

II. Thermoforming Rohacell

II. A. Introduction to thermoforming

Rohacell IG-71 polymethacrylimide foam is used as the structural support for the outer RF enclosure because of its high strength to density ratio and its long radiation length. It is also easily machined and easily thermoformed.

Rohacell foam is shipped from the manufacturer in 0.25" thick sheets. The sheets must be cut to approximately the desired length and width and then thermoformed to the correct radius using a forming fixture. The thermoforming procedure raises the temperature of the Rohacell above its forming temperature, at which point the chemical bonds that hold the shape of the foam break down. When the bonds are weakened, the Rohacell's stiffness and strength are lost and it can be molded into and held in the desired shape by the forming fixture. When the temperature falls back below the forming temperature, the chemical bonds regain their strength, and the Rohacell retains the shape the forming fixture held it in.

II. B. Materials needed

- VWR 1655D oven with Watlow 700 controller (or similar oven with air circulation that heats above 185°C)
- 37.5" x 30" x 0.25" sheet of Rohacell IG-71
- thermoforming fixture (see Appendix A)
- Zetex Plus or similar heat resistant gloves

II. C. Thermoforming procedure

1) Place the forming fixture into the oven so that the hemi-cylinder's axis penetrates through the left and right side walls of the oven and so that the fixture is convex when viewed from above.
2) Place the sheet of Rohacell into the oven vertically so that the air can circulate around it and heat it evenly.
3) Preheat the oven to 120°C.

4) Once the oven temperature has reached 120˚C, let the Rohacell dry out for approximately 3 hours.
5) Place the Rohacell into the forming fixture while in the oven so that it is held in the final shape desired.
6) Set the oven to 185˚C.
7) Let the forming fixture reach 185˚C (this takes approximately 45 minutes if the fixture's initial temperature is 120˚C or approximately 60 minutes if the fixture was allowed to cool down while positioning the Rohacell and it's initial temperature is 100˚C) and then remain at that temperature for 5 minutes. Do not let the temperature of the forming fixture or Rohacell rise above 185˚C. This is no chance the fixture temperature will rise above 185˚C if the oven is set at that temperature.
8) Set the oven temperature to room temperature (about 23˚C) and let the Rohacell and fixture cool down with the oven door closed.
9) After the fixture temperature has dropped below approximately 70˚C (about 3 hours), take the Rohacell out of the fixture.
10) Store at room temperature and a normal humidity level until ready to machine.

III. Machining Rohacell

III. A. Introduction to machining

The thermoformed Rohacell must be machined to the correct dimensions before it can be integrated into the outer RF enclosure (see Figure 2 below). Because the Rohacell has a tendency to change shape and size during its thermoforming procedure, it cannot be machined to the final enclosure dimensions before thermoforming.

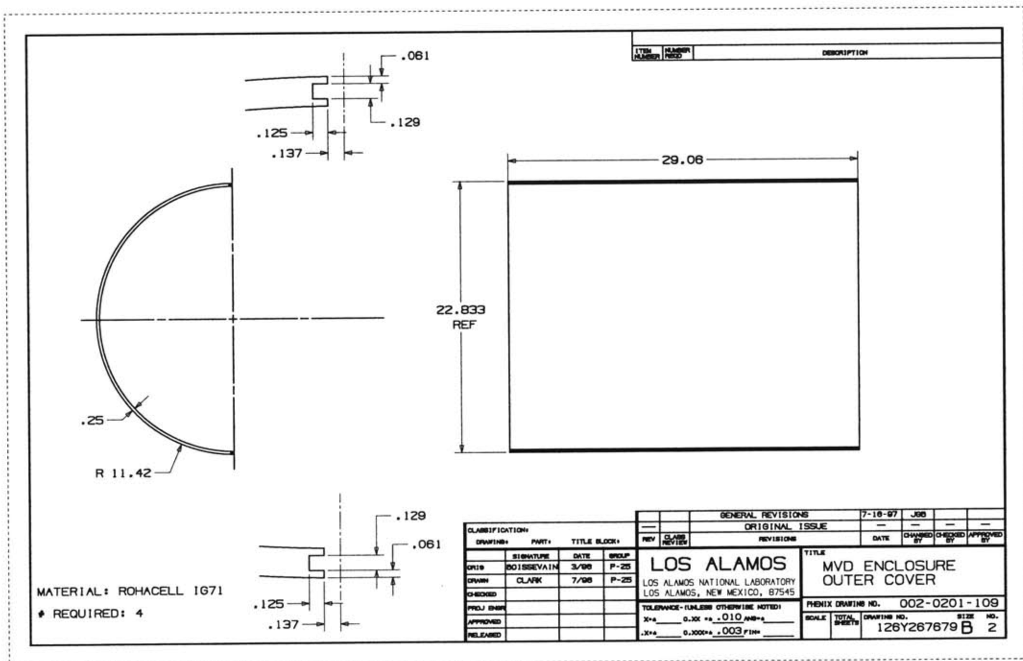


Figure 2: The Outer Enclosure's Rohacell Cover

The change in thickness due to the thermoforming process is insignificant to the effectiveness or ability to be integrated into the final enclosure unless the thermoforming procedure causes it to increase more than 125% of its original thickness. The width has a tighter tolerance, because it must be held in place by the 1/4" wide D-rings; however, the tolerances can still be met using a sharp razor blade to cut to the correct width . The tolerance on the length error is much tighter, because the 1/16" O-ring grooves in the seal strips must match up with the O-ring grooves in the D-rings. Any mismatch in the grooves could cause a tear in the airtight laminate of the inner RF enclosure. But even this tight tolerance can be attained using a razor blade if the Rohacell is aligned properly in the machining attachment for the thermoforming fixture.

There is also a small groove that needs to be made in both straight edges of the thermoformed Rohacell. Each groove will provide a firm seating for two aluminum seal strips that have the O-ring grooves machined into them. The tolerance on this groove is very tight, and a milling machine must be used to achieve the amount of accuracy required. The mill must have a travel length of at least 30", and that requirement is fairly hard to meet.

III. B. Materials needed

- a formed 37.5" x 30" x 0.25" outer Rohacell cover
- thermoforming fixture
- aluminum D-rings (see Appendix B)
- machining fixture (see Appendix C)
- sharp knife or razor blade
- masking tape
- marker or metal scribe
- a stiff, flat object (e.g. an L-square or a parallel)
- 5/16" Allen wrench
- 1/8" diameter end mill bit
- milling machine with an x-axis travel length of at least 30" and a digital readout of the milling bed's position (Ivan Taylor, TA-53, MPF-2)
- milling bed clamps to hold machining fixture in place

III. C. Machining procedure

- *Cutting the length to specification*

1) Place the D-rings and struts assembly on a flat table with 2" risers underneath the D-rings to raise it off the table.
2) Locate the marks on the inner D-rings and struts assembly which show

where the length of the curved edge of the Rohacell.

3) Tape the top edge of the Rohacell onto the D-rings so that there is foam extending past all the D-ring marks.
4) Adhere two pieces of tape along the bottom edge of the Rohacell near the D-rings so that the top edge of the tape matches up with the bottom edge of the marks on the D-rings. Make sure that the Rohacell is pulled tight around the D-rings before laying down the tape.
5) Mark the spots on the tape where the D-rings meet the tape in case the tape is adhered unleveled.
6) Tape the bottom edge of the Rohacell to the D-rings.
7) Untape the top edge of the Rohacell from the D-rings.
8) Adhere pieces of tape to the Rohacell so that they match up with the marks on the top corners of the D-rings. Make sure that the Rohacell is pulled tight around the D-rings.
9) Untape the bottom edge of the Rohacell.
10) Using the tape on the Rohacell as a marker for where to cut the length, place the Rohacell in the machining fixture, and finger tighten the bolts on the fixture.
11) Finely adjust the Rohacell so that the tape's edge is even with the flat surface on the top half of the fixture. Make sure that the top and bottom halves of the fixture are flush by pressing a parallel against the flat surface of one half and moving the other half until it hits the parallel.
12) Readjust the Rohacell if needed.
13) Tighten the fixture bolts 1/4 turn tighter with the 5/16" Allen wrench.
14) Turn the fixture upside down so that the Rohacell is hanging down, and support the unbalanced bottom half of the fixture with a 4" tall support block so that the fixture doesn't fall over.
15) Use a sharp razor to cut through the Rohacell along the bottom flat surface of the fixture.
16) Turn the fixture right side up.
17) Unbolt and remove the Rohacell from the fixture.

18) Repeat Steps #9 through #15 for the other flat edge of the Rohacell.
19) Measure the cut Rohacell against the D-rings and struts assembly to make sure the length is accurate.

- *Cutting the width to spec*

20) Measure the width of the Rohacell at several different points, subtract 29.375" from that shortest measurement. The resulting length is how much excess should be cut off of one side.
21) Use the thermoforming fixture and yellow nylon straps to align and strap down the formed Rohacell, and allow one of the curved edges to hang over the circular end of the fixture by the length calculated in Step 20. (The fixture setup is done by laying down the sheet of red rubber over the fixture surface, then laying the Rohacell on the rubber, and then tightening down the yellow nylon straps around the entire fixture. The Rohacell should be aligned so that one of the flat edges parallel to the hemi-cylinder's axis is resting on the aluminum bar that extends the length of the fixture.)
22) Use a sharp knife or razor blade to rough cut the excess Rohacell along the curved edge.
23) Use a sanding block to even up the edge. Use coarse sandpaper until there is approximately 1/16" left overhanging, and then use fine sandpaper to finish the job. To ensure a flat edge on the Rohacell, let the sanding block rub against the fixture's flat endplate surface while sanding the foam.
24) Measure the width of the Rohacell at several different spots along the curved edges, and make marks near the uncut edge exactly 29" from the cut edge.
25) Loosen the nylon straps, align the 29" marks with the other curved edge of the thermoforming fixture, and retighten the straps. Because the marks are on the opposite side of the Rohacell as the edge of the fixture, some guesswork is required, but always err on the side of the Rohacell being too wide so that you can fix the error.
26) Use the sanding block to again shave the Rohacell to be even with the flat surface of the fixture. Start with coarse sandpaper and finish with fine.

27) Remeasure the width at several points to ensure its uniformity, and resand as needed to achieve the 29" width desired.

- *Milling out the seal strip grooves*

28) Align the bottom half of the machining fixture with the milling bed and use the bed clamps to hold it in place. Use an edge finder or indicator to ensure that the fixture is parallel with the milling bed's axis of travel.
29) Zero the position of the 1/8" diameter milling bit by letting it touch the front and top surfaces of the bottom half of the fixture.
30) Place the Rohacell into the machining fixture and bolt it in so that the edge of the Rohacell is flush with the edge of the bottom fixture half. Tighten the bolts 1/4 turn past finger tight with the Allen wrench.
31) Run the milling bit down the edge of the Rohacell at Z=0.058" above the fixture's bottom surface and Y=0.132" into the Rohacell, then set Z=0.067" and run the bit back across the length of the edge. This gives a 0.134" wide by 0.132" deep groove that will allow the aluminum seal strips, conductive epoxy, and RF shielding to fit snugly together in the Rohacell's edge. Make sure that the Rohacell lips on the sides of the groove are approximately the same thickness so that the seal strips will be flush with both the inner and outer surfaces of the Rohacell.
32) Loosen the bolts and remove the machined Rohacell from the fixture.
33) Repeat Steps #15 through #17 on the unmachined flat edge.
34) Store the machined Rohacell in a safe place until ready for assembly. The thin lips of Rohacell at the edges are extremely fragile, so the machined foam should be handled very carefully to avoid breaking them off.

IV. Assembling the Outer RF Enclosure

IV. A. Introduction to assembling

Once the Rohacell has been thermoformed and machined to the correct dimensions, the assembly can begin. The assembly procedure adheres the RF shielding (aluminum foil) to the Rohacell and permanently attaches the aluminum seal strips into the grooves in the flat edges of the Rohacell as well as to the aluminum shielding.

IV. B. Materials needed

- a partner
- formed and machined outer Rohacell cover
- two 44" x 34" 1/2mil sheets of aluminum foil at least
- two 2mil sheets of Dielectric Polymers NT 988-2 dry transfer adhesive at least 39" x 30"
- the thermoforming fixture
- the large rubber sheet used in the machining procedure
- a sharp razor blade
- a tape measure
- masking tape
- thin, clean cloth gloves (clean room gloves)
- a flat, cutting board surface (cardboard works well)
- a strip of the dry adhesive's backing at least 30" x 1/2"
- a straight-edged strip of metal 1/8" wide
- the rolling bar (a smooth cylinder at least 35" long and between 1" and 3" diameter)
- conductive epoxy
- a few cotton swabs or a small plastic spatula to spread out the epoxy
- two inner seal strips (see Appendix D)
- two outer seal strips (see Appendix D)

IV. C. Assembling procedure

- *Adhere the radiation shielding to the outer surface of the Rohacell*

1) Lay down one of the sheets of aluminum foil on the cardboard and tape the edges taut.
2) With your partner's help, cut out one of the sheets of adhesive and lay it down centered and smoothed on the foil. The best way to lay the adhesive down smoothly is to adhere one corner and smooth the rest outward from that corner.
3) Run your finger along the edge of the adhesive's backing to ensure that it is firmly adhered to the foil.
4) Peal the backing off the adhesive. This is best done by pealing from one corner and making sure that the backing stays as parallel as possible with the cardboard, so that the aluminum foil is not stretched.
5) Align one of the flat, grooved edges of the Rohacell with one of the shorter edges of the adhesive. Place the corner edge of the Rohacell on the adhesive approximately 1/2" from the adhesive's edge so that the larger radius surface of the Rohacell can be rolled onto the adhesive. Make sure to line up the Rohacell so that it will not roll off the adhesive.
6) Put a straight-edged strip of the adhesive backing over the 1/2" of exposed adhesive to prevent it from adhering to the cardboard or the inner surface of the Rohacell.
7) While holding the Rohacell upright so that it does not pull on and stretch the foil, have your partner cut the masking tape from the foil around the area where the Rohacell is adhered.
8) Roll the Rohacell onto the adhesive keeping the foil as taut as possible while your partner cuts the masking tape from the foil around the area you are rolling.
9) Repeat Step #6 for the exposed adhesive at the other grooved edge.
10) Cut the excess foil from the two curved edges of the Rohacell. To avoid tearing the foil, press down on the smaller radius surface of the Rohacell and cut through the foil at the point where the Rohacell is contacting the

cardboard.

11) Cut a piece of the adhesive backing into a strip that is at least 30" x 1/2" and make sure that one edge is straight.
12) Have your partner hold the Rohacell upright so that the groove in the Rohacell is parallel with the cardboard.
13) Align the straight edge of the backing with one of the straight edges of the Rohacell and adhere it.
14) Align and tape down the 1/8" wide metal strip with the straight edge of the Rohacell and backing.
15) Use a sharp razor blade to cut through the backing, adhesive, and foil along the outer edge of the metal strip, while keeping the strip in place with your finger.
16) Remove the metal strip and peal off the backing (parallel to the foil).
17) Make several passes with your fingertip to fold the foil over the Rohacell lip and into the groove.
18) Use the razor blade to firmly adhere the foil to the inside surface of the groove.
19) Repeat Steps #11 through #18 for the other flat edge's excess foil.

- *Adhere the radiation shielding to the inner surface of the Rohacell*

20) Repeat Steps #1 through #4 to lay down the foil and adhesive that will be adhered onto the smaller radius surface of the Rohacell.
21) Cut the masking tape off of both long sides and one of the short sides of the foil.
22) Adhere a strip of adhesive backing over approximately 1/2" of the adhesive on the shorter untaped foil edge.
23) Align and adhere the edge of the Rohacell with the edge of the adhesive backing so that the adhesive can be rolled onto the smaller radius surface.
24) With your partner holding the Rohacell upright, use the rolling bar to roll the foil and adhesive onto the first few inches of the smaller radius surface of the Rohacell. Keep the foil tight while rolling.

25) Untape the last edge of the foil, have your partner hold the loose foil up and off of the cardboard, turn the Rohacell so that the bare surface is facing you, and have your partner climb up onto the table for more ease in holding up the foil.
26) Continue rolling the foil onto the Rohacell until you have rolled it past the other grooved edge. Have your partner keep the foil taut as it is rolled on, and put tension on the foil along the length of the rolling bar to minimize wrinkles.
27) Adhere a straight-edged strip of adhesive backing to the exposed adhesive at the grooved edge of the Rohacell to keep it from adhering to the larger radius Rohacell surface or the cardboard.
28) Set up the thermoforming fixture with the large rubber sheet on top, and place the shielded Rohacell on the rubber sheet.
29) Use a sharp razor blade to cut the excess foil off of the two curved edges of the Rohacell. Put pressure on the Rohacell close to the area being cut off to make a clean, straight cut.
30) Repeat Steps #14 through #18 to adhere the shielding to the insides of the grooves, but keep the Rohacell on the thermoforming fixture to cut the foil on the two straight edges to the correct 1/8" width.
31) Use clean, white gloves or a clean, soft cloth to smooth the foil out on the Rohacell and remove any fingerprints.•

- *Attach the seal strips*

32) If you are satisfied with the way the shielding rolled onto the Rohacell (satisfied with the amount of wrinkling), then mix up a small (approximately 1oz.) amount of the conductive epoxy.
33) With a cotton swab, spread a very thin coat of the epoxy on the flat surfaces of one inner and one outer seal strip that will touch each other when assembled.
34) Attach the seal strips together, clamp them, and let them dry. Make sure to wipe off any excess epoxy.

35) Mix up more of the conductive epoxy.

36) Put the epoxy on the lower surfaces of the seal strips.

37) Push the seal strips into the groove in the Rohacell. Start by pressing one end of the seal strip into the groove and then move down the length of the strips pushing the rest in. Be sure that the seal strip with the O-ring groove that penetrates through the side walls of the strip is nearest the axis of the hemi-cylinder with the cut outs pointing towards the axis.

38) Clamp the seal strips in the correct place and let the epoxy dry. Wipe off any excess epoxy.

39) Repeat Steps #32 through #38 for the other seal strip groove.

V. Integrating the Outer Enclosure with the MVD

V. A. Introduction to integration

The integration of the Outer Enclosure with the rest of the MVD is one of the last MVD assembly steps. Only the Inner Enclosure is installed later in the process. Consequently, the integration procedure must be very safe and reliable so as to insure non-interference with the MVD electronics.

Fortunately, the integration of the Outer Enclosure with the rest of the MVD is fairly simple and straightforward. The procedure involves four steps: firmly securing the MVD to protect against bumps, seating the enclosure in the pocket formed by the MVD's aluminum frame (the D-rings and struts), aligning the O-ring grooves in the seal strips with the O-ring grooves in the D-rings, and then screwing the outer enclosure retaining rings into place.

V. B. Materials needed

- ten 1/4" long aluminum 4-40 flat head screws
- a small flathead screwdriver
- two outer retaining rings (see Appendix E)
- an assembled Outer RF Enclosure
- the holding fixture (see Appendix F)

V. C. Integration procedure

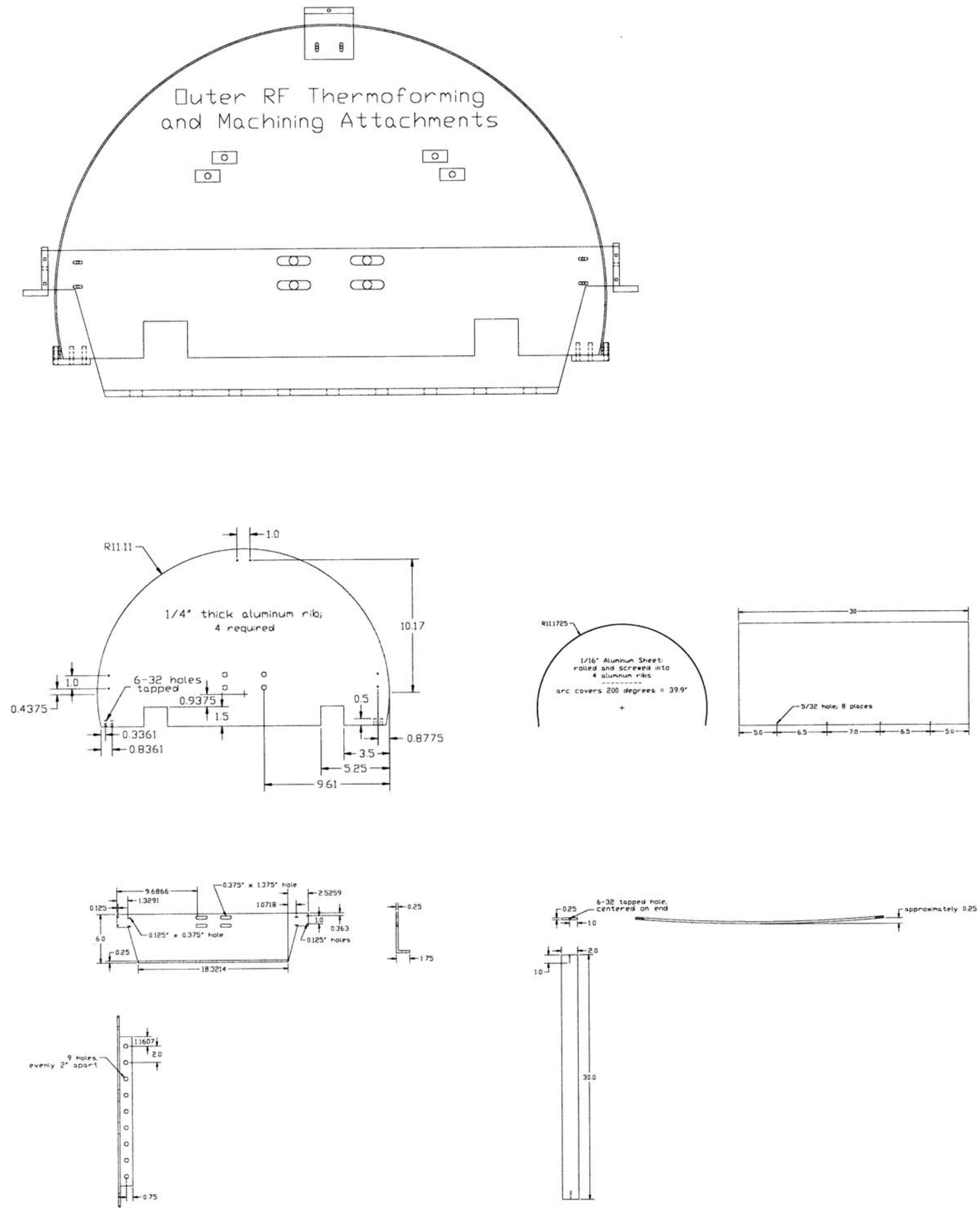
1) Secure the MVD in the holding fixture.
2) Place the assembled Outer Enclosure on top of the inner set of D-rings and in between the outer set of D-rings.
3) Align one of the seal strip edges so that the O-ring grooves in the seal strips run smoothly into the O-ring grooves in the D-rings.
4) Screw two flat head 4-40 screws through one of the retaining rings and into the two tapped holes in the D-ring closest to the aligned edge.
5) Repeat Step #4 for the other retaining ring holes closest to the aligned edge.
6) Make sure that the retaining ring makes good contact with the radiation

shield. If the rings cause a little compression of the Rohacell, then good contact is insured. If the Rohacell is not held firmly in place, then put a strip(s) of indium wire in between the loose retaining ring(s) and foil and repeat Steps #3 through #5.

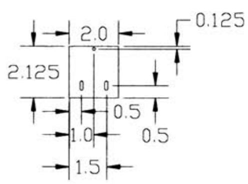
7) Make sure that the O-ring grooves in the other seal strip edge of the Rohacell match up with their corresponding O-ring grooves in the D-rings.

8) Screw in the rest of the screws starting with the ones closest to the seal strips and moving towards the middle of the Rohacell.

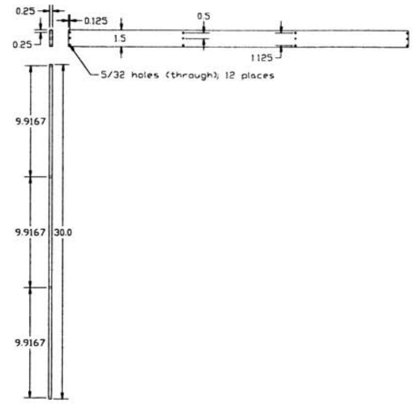
Appendix A: The Outer Enclosure Thermoforming Fixture and Machining Attachments



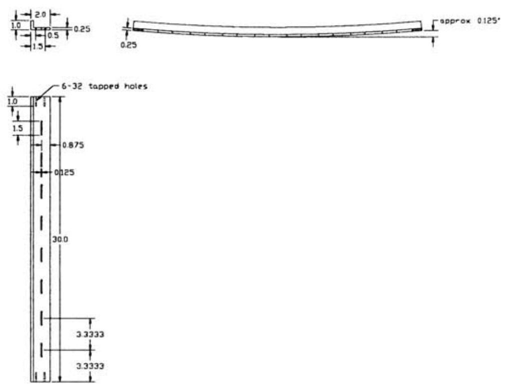
0.25
0.125
0.375
0.125



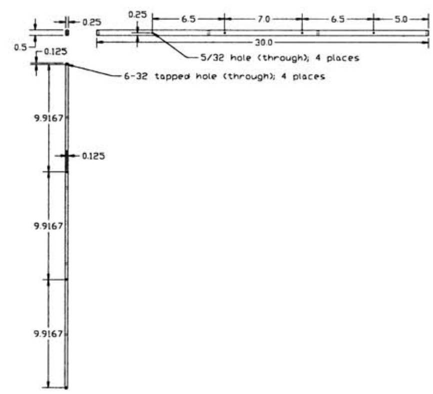
2.0
0.125
2.125
0.5
1.0
0.5
1.5



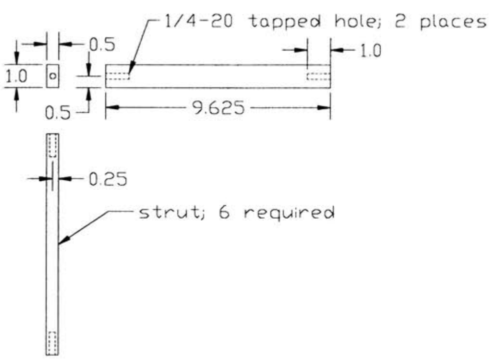
0.25
0.125
0.5
0.25
1.5
1.125
5/32 holes (through); 12 places
9.9167
9.9167
30.0
9.9167



2.0
1.0
0.5
0.25
1.5
approx 0.125"
0.25
6-32 tapped holes
1.0
1.5
0.875
0.125
30.0
3.3333
3.3333

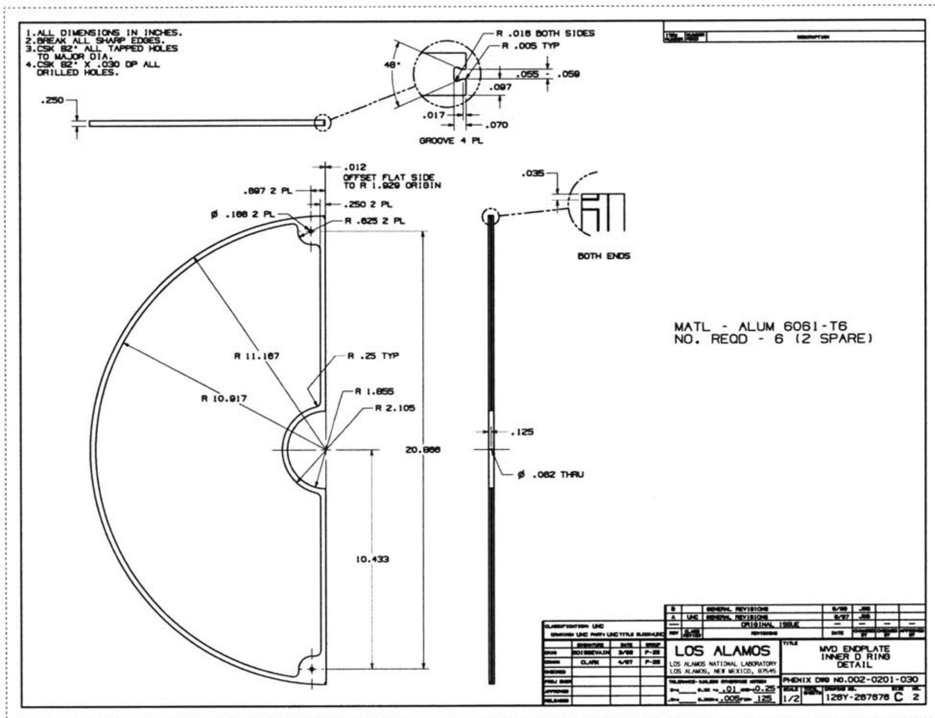


0.25
0.25
6.5
7.0
6.5
5.0
30.0
0.5
0.125
5/32 hole (through); 4 places
6-32 tapped hole (through); 4 places
9.9167
0.125
9.9167
9.9167

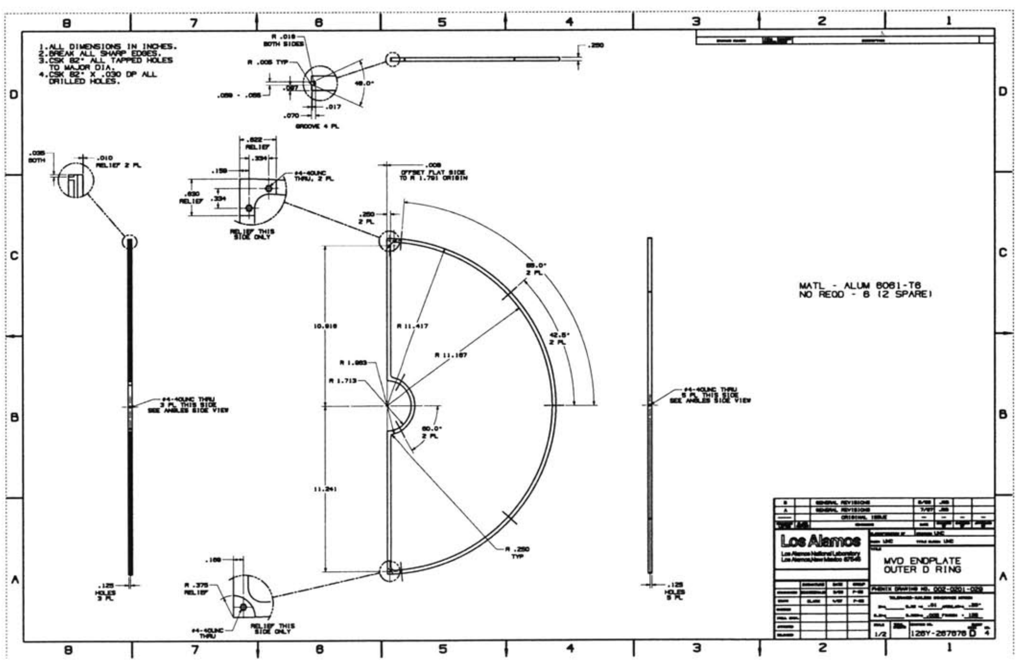


1/4-20 tapped hole; 2 places
0.5
1.0
1.0
0.5
9.625
0.25
strut; 6 required

Appendix B: The Endplate's D-rings

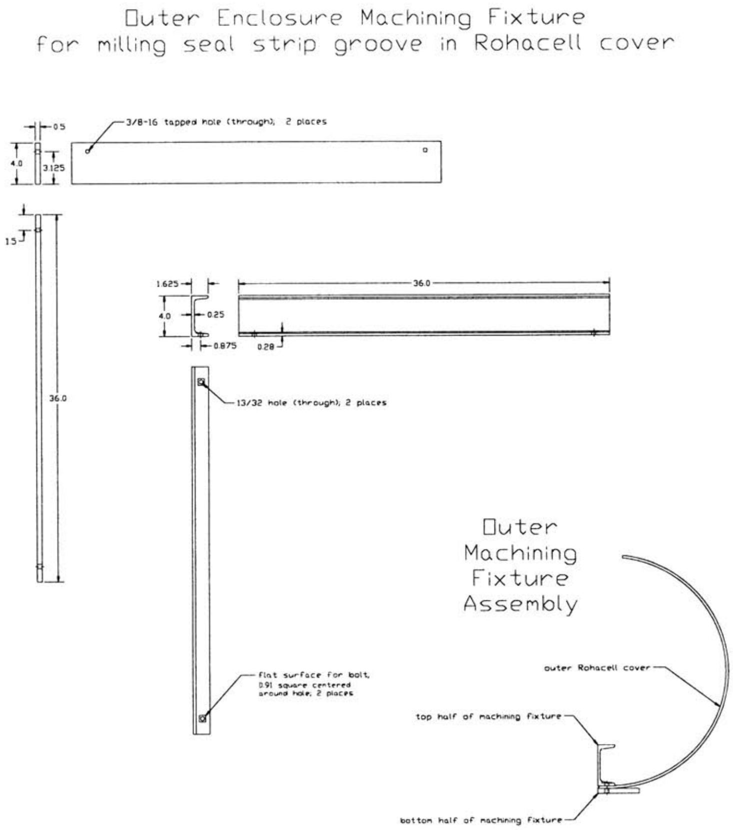


The Inner D-ring

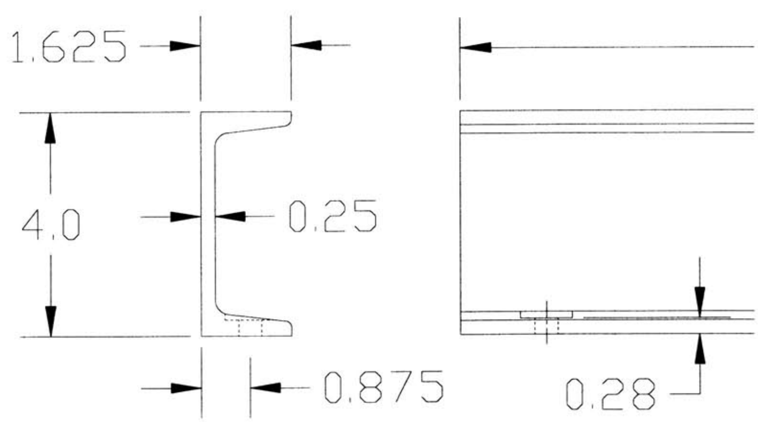


The Outer D-ring

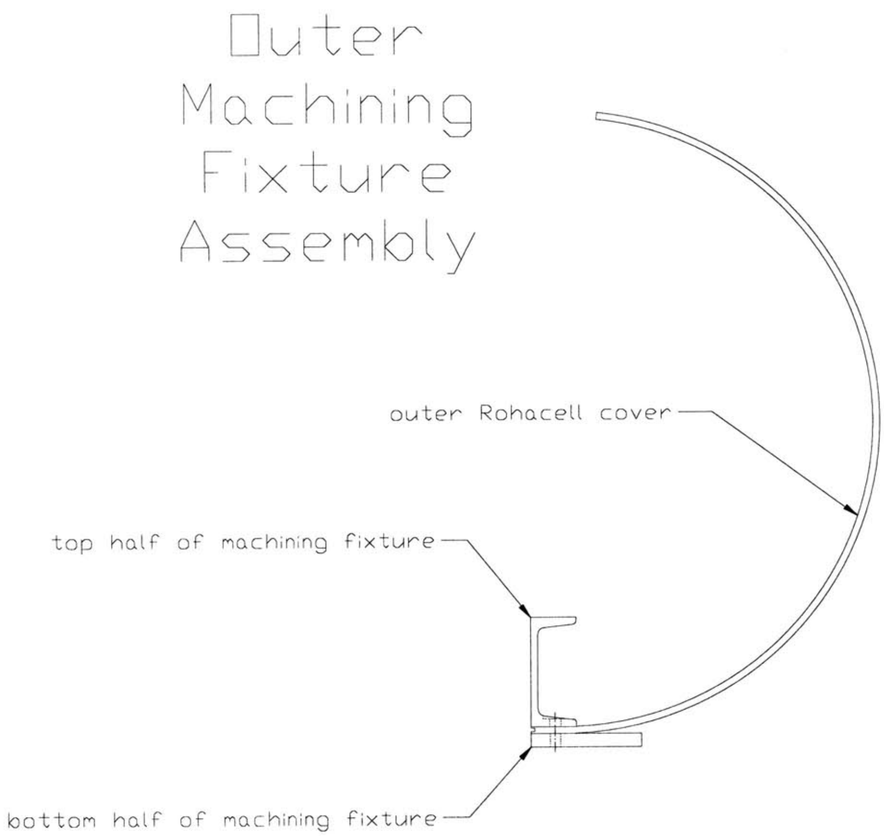
Appendix C: The Outer Enclosure Machining Fixture



Parts and Assembly

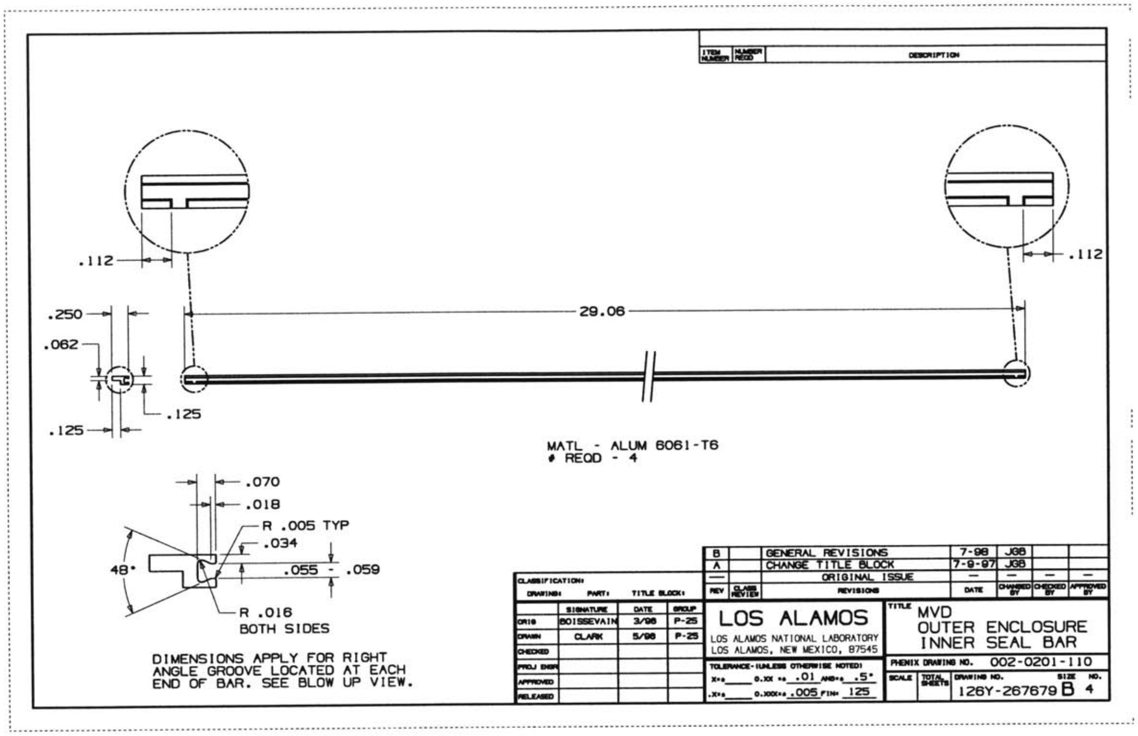


Detail of hole positioning

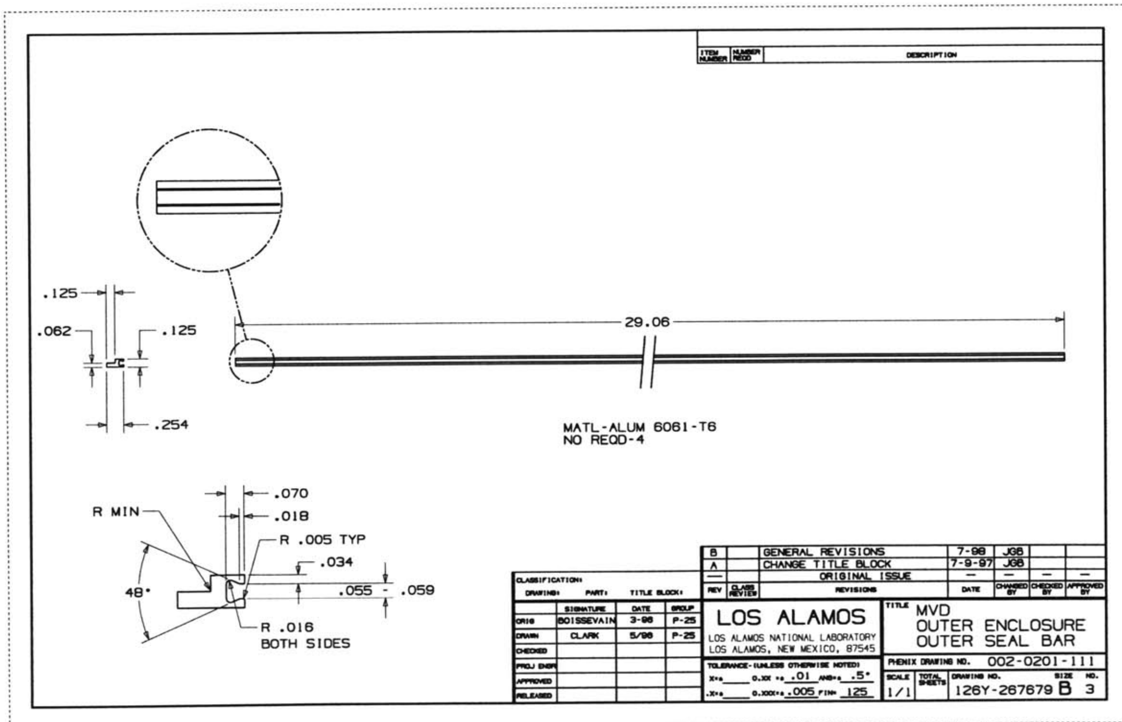


Labeled Assembly

Appendix D: The Outer Enclosure Seal Strips

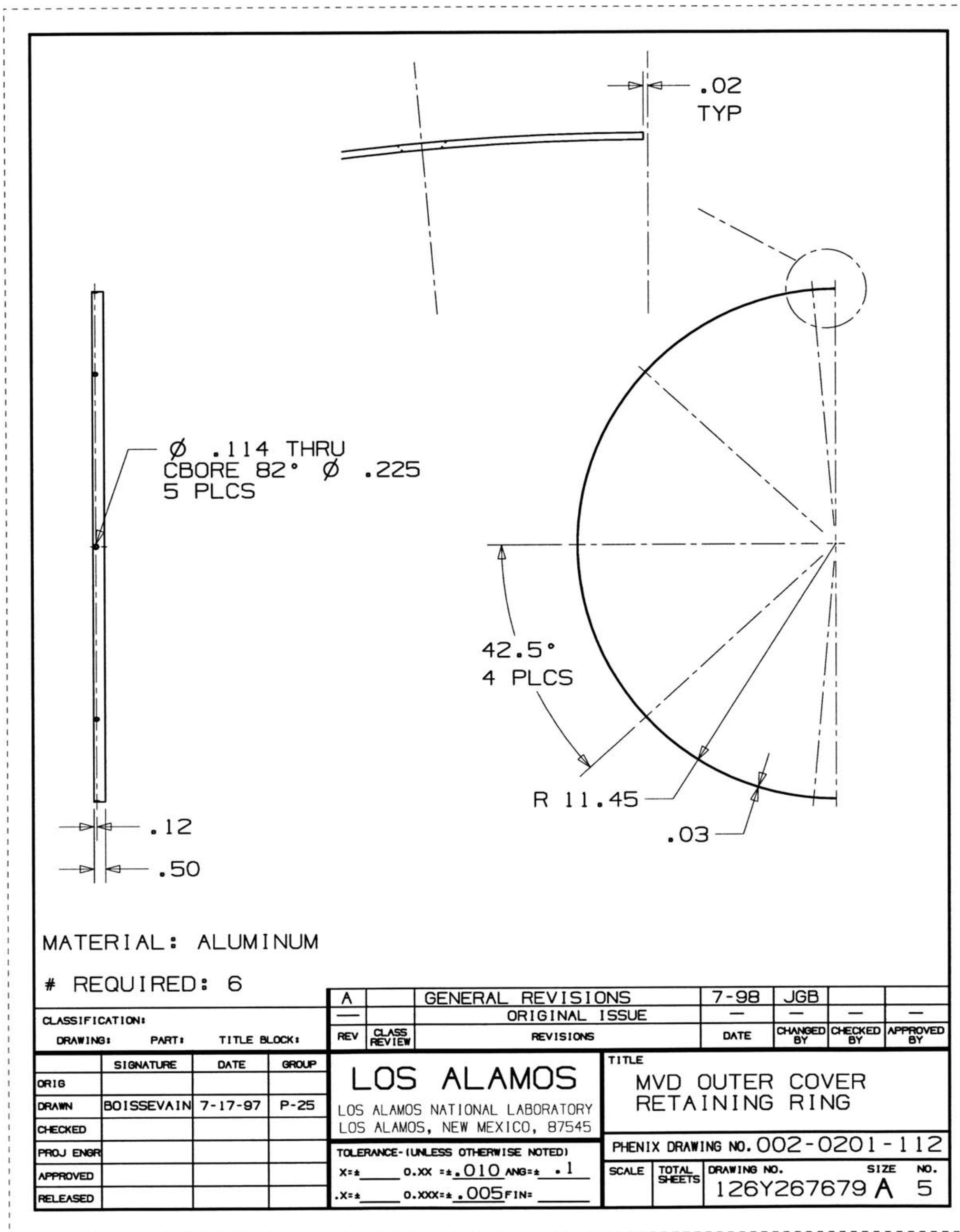


The Inner Seal Strip



The Outer Seal Strip

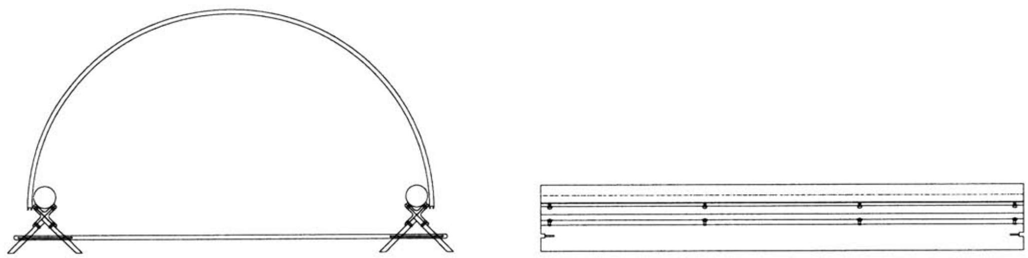
Appendix E: The Outer Enclosure Retaining Rings

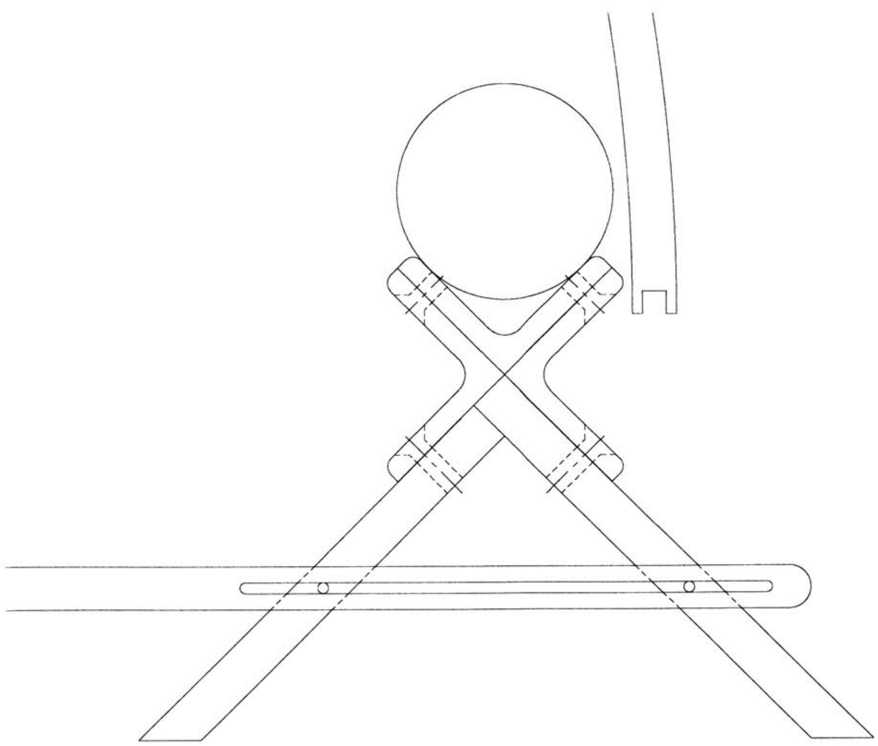


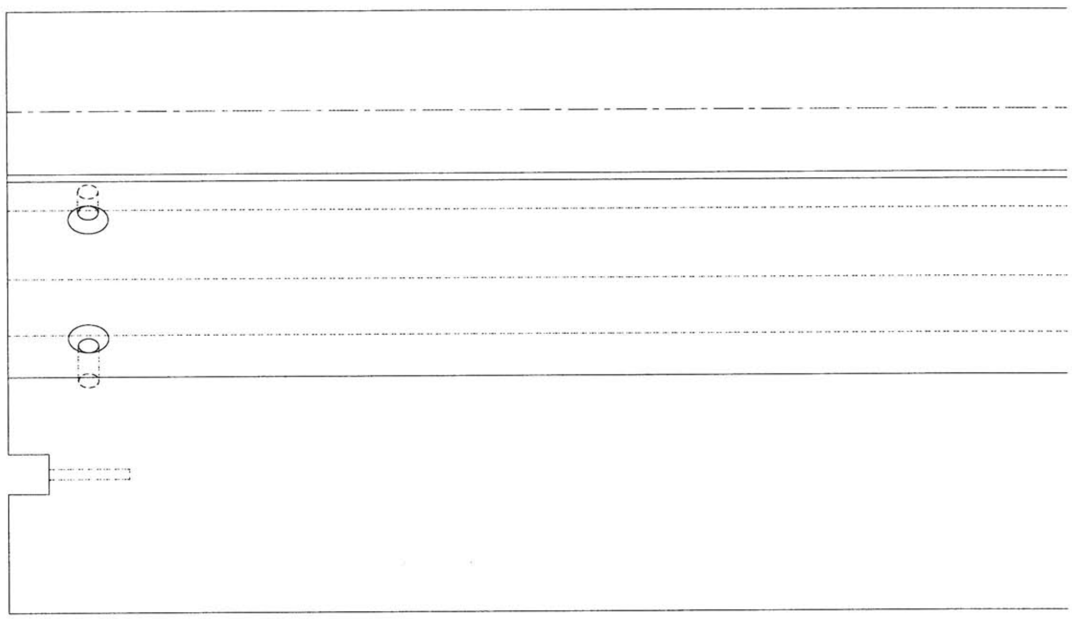
The Outer Enclosure Retaining Ring

Appendix F: Conceptual drawings of the MVD Holding Fixture accommodating the integration of the Outer Enclosure

MVD Holding Fixture
(to be used in Outer RF Enclosure installation)







8.5 Prototype RF Enclosure attenuation test data

Summary of RF enclosure attenuation tests

1) Received amplitude results could not be reproduced after the enclosure was rotated. The average change in amplitude was 7.5dBm and the standard deviation was 3dBm.
2) Received amplitude results were not symmetrical about the enclosure. The average standard deviation between measurements at different angles was 4.3dBm.
3) When the enclosure remained in a fixed position, the average standard deviation of the received amplitude was small at 0.5dBm.
4) The transmission/ reception efficiency of the antennae at 10MHz was too low to measure the amount of attenuation provided by the shielding.
5) At 80MHz, decreasing the distance between the receiving and transmitting antennae by 50% caused an average 11dBm increase in the received amplitude.

Average Delta Repeated Angles
7.5

St. Dev. Delta Repeated Angles
3.0413813

Average St. Dev. Fixed Position
0.42775652

Average St. Dev. Non-repeated Angles
4.3120129

% decrease of dist. between antennae
50.364964

Average increase in amplitude
11.296949

Frequency (MHz)	Attenuation (dBm)
290	54.714286
125	37.862154
80	60.141515
40	68.700111

Angle (degrees)	Attenuation (dBm)
0	53.5
45	52.5
90	55.5
135	58.5
180	53.5
225	53
135	47.5
135	56
180	58
225	56.5
270	65.5
315	56
360	63
45	47.5
90	49.5

RF Enclosure Shielding Test Data (all inclusive)

Transmitting Info			Receiving Info								
Antenna Length (cm)	Frquency (MHz)	Amplitude (dBm)	Antenna Length (cm)	Distance between antennae (cm)	Enclosure Angle	Antenna attached?	Shielded?	Amplitude (dBm)	Average Amplitude (dBm)	Fluctuation (dBm)	Background Level (dBm)
28	290	15	27	136	0	Yes	Yes	-71	-71	3.0	-94
28	290	15	27	136	45	Yes	Yes	-70		0.5	-94
28	290	15	27	136	90	Yes	Yes	-73		1.0	-94
28	290	15	27	136	135	Yes	Yes	-76		1.0	-94
28	290	15	27	136	180	Yes	Yes	-71		1.0	-94
28	290	15	27	136	225	Yes	Yes	-70		0.5	-94
28	290	15	27	136	135	Yes	Yes	-65		1.0	-94
28	290	15	27	136	135	Yes	Yes	-74	-74	0.5	-94
28	290	15	27	136	180	Yes	Yes	-76		0.5	-94
28	290	15	27	136	225	Yes	Yes	-74		1.0	-94
28	290	15	27	136	270	Yes	Yes	-83		1.0	-94
28	290	15	27	136	315	Yes	Yes	-74		1.0	-94
28	290	15	27	136	360	Yes	Yes	-80		2.0	-94
28	290	15	27	136	45	Yes	Yes	-65		1.0	-94
28	290	15	27	136	90	Yes	Yes	-67		1.0	-94
28	290	15	27	137	135	Yes	No	-18	-18	1.0	-94
60	125	15	60	137	135	Yes	No	-16	-16	1.0	-94
60	125	15	60	137	135	Yes	Yes	-66	-71	0.5	-94
60	125	15	60	137	140	Yes	Yes	-74		1.0	-94
60	125	15	60	137	135	Yes	Yes	-72		1.0	-94
60	125	15	60	137	135	Yes	Yes	-87	-83	1.0	-94
60	125	15	60	137	180	Yes	Yes	-80		1.0	-94
60	125	15	60	137	135	Yes	Yes	-81		1.0	-94
60	125	15	60	137	135	Yes	Yes	-58	-59	0.4	-94
60	125	15	60	137	135	Yes	Yes	-60			-94
60	125	15	60	137	135	Yes	Yes	-59			-94
60	125	15	60	137	135	Yes	Yes	-59			-94
60	125	15	60	137	135	Yes	Yes	-60			-94
60	125	15	60	137	135	Yes	Yes	-60			-94
60	125	15	60	137	135	Yes	Yes	-59			-94
60	125	15	60	137	135	Yes	Yes	-59			-94
60	125	15	60	137	135	Yes	Yes	-60			-94
60	125	15	60	137	135	Yes	Yes	-59			-94
60	125	15	60	137	135	Yes	Yes	-60			-94
60	125	15	60	137	135	Yes	Yes	-59			-94
60	125	15	60	137	135	Yes	Yes	-60			-94
60	125	15	60	137	135	No	No	-91	-91	1.5	-94
60	125	15	60	137	135	No	No	-92			-94
60	125	15	60	137	135	No	No	-93			-94
60	125	15	60	137	135	No	No	-91			-94
60	125	15	60	137	135	No	No	-92			-94
60	125	15	60	137	135	No	No	-92			-94
60	125	15	60	137	135	No	No	-90			-94
60	125	15	60	137	135	No	No	-93			-94
60	125	15	60	137	135	No	No	-88			-94
60	125	15	60	137	135	Yes	No	-27	-27	0.2	-94
60	125	15	60	137	135	Yes	No	-27			-94
60	125	15	60	137	135	Yes	No	-27			-94
60	125	15	60	137	135	Yes	No	-27			-94
60	125	15	60	137	135	Yes	No	-27			-94
60	125	15	60	137	135	Yes	No	-27			-94
60	125	15	60	137	135	Yes	No	-27			-94
60	125	15	60	137	135	Yes	No	-27			-94
60	125	15	60	137	135	Yes	No	-27			-94
60	125	15	60	137	135	Yes	No	-27			-94
60	125	15	60	131	135	Yes	No	-27	-27	0.2	-94
60	125	15	60	131	135	Yes	No	-27			-94
60	125	15	60	131	135	Yes	No	-27			-94
60	125	15	60	131	135	Yes	No	-27			-94

60	125	15	60	131	135	Yes	No	-27			-94
60	125	15	60	131	135	Yes	No	-27			-94
60	125	15	60	131	135	Yes	No	-27			-94
60	80	15	60	137	135	Yes	Yes	-89	-89	0.9	-94
60	80	15	60	137	135	Yes	Yes	-87			-94
60	80	15	60	137	135	Yes	Yes	-88			-94
60	80	15	60	137	135	Yes	Yes	-87			-94
60	80	15	60	137	135	Yes	Yes	-88			-94
60	80	15	60	137	135	Yes	Yes	-90			-94
60	80	15	60	137	135	Yes	Yes	-89			-94
60	80	15	60	137	135	Yes	Yes	-89			-94
60	80	15	60	137	135	Yes	Yes	-90			-94
60	80	15	60	137	135	Yes	Yes	-89			-94
60	80	15	60	137	135	Yes	Yes	-89			-94
60	80	15	60	137	135	No	No	-85	-86	0.9	-94
60	80	15	60	137	135	No	No	-87			-94
60	80	15	60	137	135	No	No	-86			-94
60	80	15	60	137	135	No	No	-87			-94
60	80	15	60	137	135	No	No	-87			-94
60	80	15	60	68	135	No	No	-76	-76	0.6	-94
60	80	15	60	68	135	No	No	-77			-94
60	80	15	60	68	135	No	No	-75			-94
60	80	15	60	68	135	No	No	-75			-94
60	80	15	60	68	135	No	No	-75			-94
60	80	15	60	68	135	Yes	No	-16	-16	0.1	-94
60	80	15	60	68	135	Yes	No	-16			-94
60	80	15	60	68	135	Yes	No	-16			-94
60	80	15	60	68	135	Yes	No	-16			-94
60	80	15	60	68	135	Yes	No	-16			-94
60	80	15	60	68	135	Yes	Yes	-79	-79	0.3	-94
60	80	15	60	68	135	Yes	Yes	-78			-94
60	80	15	60	68	135	Yes	Yes	-79			-94
60	80	15	60	68	135	Yes	Yes	-78			-94
60	80	15	60	68	135	Yes	Yes	-79			-94
60	80	15	60	137	135	Yes	No	-28	-29	0.1	-94
60	80	15	60	137	135	Yes	No	-28			-94
60	80	15	60	137	135	Yes	No	-28			-94
60	80	15	60	137	135	Yes	No	-29			-94
60	80	15	60	137	135	Yes	No	-29			-94
60	80	15	60	137	135	Yes	No	-28			-94
60	10	15	60	131	135	Yes	No	-40	-40	0.1	-94
60	10	15	60	131	135	Yes	No	-40			-94
60	10	15	60	131	135	Yes	No	-40			-94
60	10	15	60	131	135	Yes	No	-40			-94
60	10	15	60	131	135	Yes	No	-40			-94
60	10	15	60	131	135	Yes	No	-40			-94
60	10	15	60	131	135	Yes	No	-40			-94
60	10	15	60	131	135	Yes	No	-40			-94
60	10	15	60	137	135	Yes	No	-40	-40	0.0	-94
60	10	15	60	137	135	Yes	No	-40			-94
60	10	15	60	137	135	Yes	No	-40			-94
60	10	15	60	137	135	Yes	No	-40			-94
60	10	15	60	137	135	Yes	No	-40			-94
60	10	15	60	137	135	Yes	No	-40			-94
60	10	15	60	137	135	Yes	No	-40			-94
60	10	15	60	137	135	Yes	No	-40			-94
60	10	15	60	137	135	Yes	No	-40			-94
60	10	15	60	137	135	Yes	No	-40			-94
60	10	15	60	137	135	Yes	Yes	-94		1.0	-94
60	10	15	60	137	135	No	No	-94		1.0	-94
60	40	15	60	137	135	Yes	Yes	-94		1.0	-94

60	40	15	60	137	135	No	No	−94		1.0	−94
60	40	15	60	137	135	Yes	No	−42	−41	0.2	−94
60	40	15	60	137	135	Yes	No	−42			−94
60	40	15	60	137	135	Yes	No	−42			−94
60	40	15	60	137	135	Yes	No	−42			−94
60	40	15	60	137	135	Yes	No	−42			−94
60	40	15	60	137	135	Yes	No	−42			−94
60	40	15	60	137	135	Yes	No	−41			−94
60	40	15	60	137	135	Yes	No	−41			−94
60	40	15	60	137	135	Yes	No	−41			−94
60	40	15	60	137	135	Yes	No	−41			−94
185	40	15	60	137	135	Yes	No	−18	−18	0.3	−94
185	40	15	60	137	135	Yes	No	−18			−94
185	40	15	60	137	135	Yes	No	−18			−94
185	40	15	60	137	135	Yes	No	−19			−94
185	40	15	60	137	135	Yes	No	−18			−94
185	40	15	60	137	135	Yes	No	−18			−94
185	40	15	60	137	135	Yes	No	−18			−94
185	40	15	60	137	135	Yes	No	−18			−94
185	40	15	60	137	135	Yes	No	−18			−94
185	40	15	60	137	135	Yes	No	−18			−94
185	40	15	60	137	135	Yes	Yes	−87	−87	0.7	−94
185	40	15	60	137	135	Yes	Yes	−88			−94
185	40	15	60	137	135	Yes	Yes	−88			−94
185	40	15	60	137	135	Yes	Yes	−87			−94
185	40	15	60	137	135	Yes	Yes	−87			−94
185	40	15	60	137	135	Yes	Yes	−86			−94
185	40	15	60	137	135	Yes	Yes	−86			−94
185	40	15	60	137	135	Yes	Yes	−86			−94
185	40	15	60	137	135	Yes	Yes	−87			−94
185	40	15	60	137	135	No	No	−91	−92	0.9	−94
185	40	15	60	137	135	No	No	−93			−94
185	40	15	60	137	135	No	No	−92			−94
185	40	15	60	137	135	No	No	−93			−94
185	40	15	60	137	135	No	No	−93			−94
185	40	15	60	137	135	No	No	−91			−94
185	40	15	60	137	135	No	No	−93			−94
185	40	15	60	137	135	No	No	−93			−94
185	40	15	60	137	135	No	No	−92			−94

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