

*An Introduction to
Solar Vehicle Mold Design and Construction*



Al Majkrzak

Spring 2005

An Introduction to Solar Vehicle Mold Design and Construction

Al Majkrzak

Spring 2005

ME 5090

Dr. Starr



Figure 1: Borealis 3 Bottom Mold during Finishing Run at PaR Systems

Table of Contents

<i>Introduction</i>	3
<i>Shell Design</i>	3
<i>Mold Design</i>	5
<i>Mold Machining</i>	11
<i>Mold Finishing</i>	16
<i>Appendix</i>	
<i>Contact List</i>	20
<i>General Plastics Foam Inventory</i>	23
<i>Mold Base Bill of Materials</i>	23
<i>Rolla Solar Miner IV Paper</i>	24
<i>General Plastics Last-A-Foam Guide</i>	30

Introduction

Through ten years of work the University of Minnesota Solar Vehicle Project has succeeded in producing six world class cars. As this paper is written the Project is in the midst of its seventh, Borealis 3. For all but the first car, Aurora 1, the body shells have been produced using a direct to mold process consisting of dense polyurethane foam and primer. Six sets of foam molds have been produced by the team over the years each meeting with varying levels of success.

It is the purpose of this paper to explain the procedure employed by the team so that it may not be lost. It has been the observation of the author that great works and technical skill are easily and routinely forgotten by the project. Although this paper may be viewed as a basic recipe for construction of a shell mold it may be better utilized as a starting point for ones own car. The procedures included herein should be read cautiously by the reader and questioned continually along the way.

Shell Design

The quality of the final shell is only as good as the quality of the computer model it is built from. There are two basic CAD techniques that may be employed to create shell geometry. These two methods are solid modeling and surface modeling. It will be assumed in this paper that the reader employs surface modeling to create the car model. Surface model is much more conducive to the type and complexity of surfaces that need to be created to produce a high class shell model.

For Borealis 3 we employed Pro Engineer Wildfire to create the shell geometry. A wireframe of datum curves was drawn to create a skeleton for the shell. Next, boundary surfaces were created and draped over the datum curves to create the outer skin of the car. The procedure, while in the computer, is similar to the method of frame-and-fabric construction used to create aircraft of WWI vintage. It is advisable to look at the CAD files of past cars to see the specific features used to create the complex shell geometries.

In regards to machining one must remember that the CAD/CAM system will faithfully reproduce the designers shape. That means every error, however slight, will appear fully in the final mold. The designer, therefore, must make every effort to limit the number and severity of non-ideal surfacing. Two common errors are surface bowing and non-tangent surface boundaries.

Surface bowing occurs when the center of a surface bows either up or down relative to the surface's boundary curves. This causes surfaces to bulge outward or inward from the car and can degrade the aerodynamics of the vehicle.

Non-tangent surface boundaries occur when two separate surfaces share a common boundary curve. Although the surfaces may intersect at the curve, they are not tangent to each other. This can cause bumps and ridges at locations where datum curves have been drawn.

In addition to the basic aerodynamic shape of the shell the CAD file should also include any datums and flanges that the designer wishes to be cut into the mold. The mold flange consists of a ribbon that is normal to the split between the top and bottom shells. The mold flange is cut into the final molds and is used during shell layup for vacuum bagging. After shell production the flange serves as a common curve that the top and bottom shells are trimmed to. This facilitates joining of the two separate parts. Also thin datum curves may be cut into the mold on the flange to indicate car centerlines, bulkhead locations, or other important dimensions. Figure 2 shows a picture of the datum curves cut into the Borealis 3's bottom shell. The curves were cut $1/8^{\text{th}}$ wide and 0.020 deep into the foam mold.

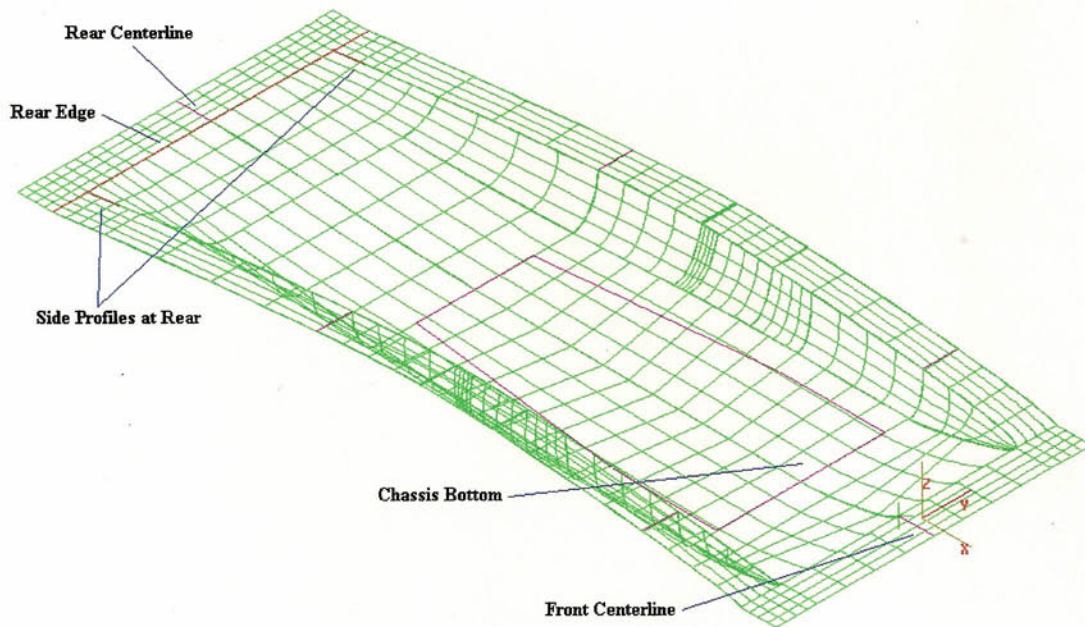


Figure 2: Borealis 3 Bottom Shell Datums

After the shells have been produced they can be infuriatingly difficult to dimension or measure with any accuracy. Few, if any, straight lines appear on the final shell to serve as a baseline. Small lines or holes cut into the mold will appear in the final shell and greatly help final car assembly. These cuts may be placed in areas which will eventually be fully cut away (canopy, chassis bottom, wheel cutouts, etc.).

Mold Design

In order to create the desired shape for a shell a mold must be constructed. There are two basic types of molds; male molds and female molds. The choice between the two depends on which surface of the part one wishes to control. The control surface is the surface of the finished part which was in contact with the surface of the mold. The controlled surface will have a much higher surface quality (smoothness) and much higher dimensional accuracy. Figure 3 presents a drawing for clarity. Without exception all of Minnesota's body molds have been female molds. This is because we wish the outer surface of the car (the one in contact with the air stream) to be smooth and dimensionally accurate. The inner surface of the shell is not as critical in regards to surface finish or tolerance.

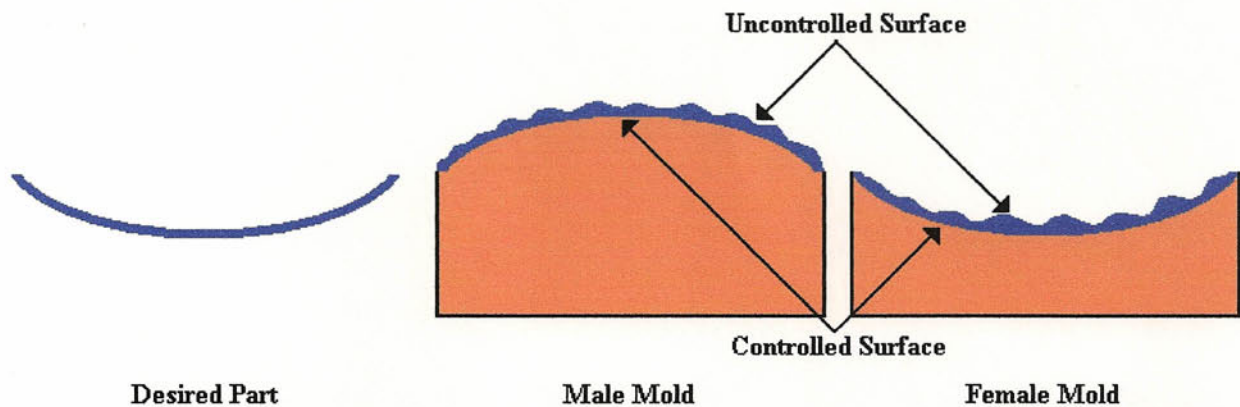


Figure 3: Male and Female Mold Schematic

Direct to Mold vs. Plug-Mold

After one has decided what type of mold to produce it is necessary to choose a process to produce the mold. The two main processes for mold production are direct to mold and plug-mold. In the direct to mold process the mold in its final configuration (either male or female) is machined directly into the tooling material. The mold's surface is then finished and sealed and then the final part is created directly off of this tool. In plug-mold construction a plug of the opposite gender is machined by the mill. The plug is then finished and sealed. The final mold is then created by laying up layers of composite over the buck. The finished mold is then pulled from the buck and polished to the desired surface finish. The final part is then created from this mold. Figures 4 and 5 present both processes.

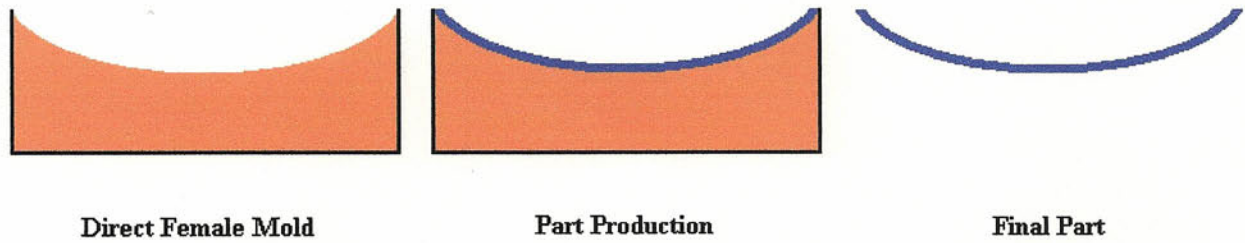


Figure 4: Direct to Mold Production

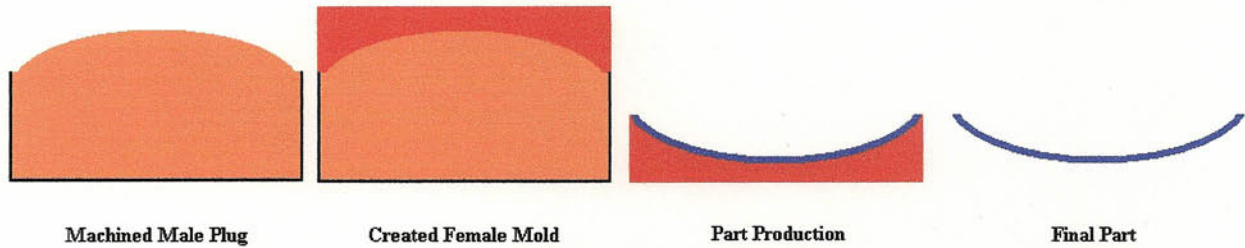


Figure 5: Plug-Mold Production

In industry plug-mold production is more common than direct to mold. This is because many times a quality final mold is desired that can produce dozens of parts from the same mold. This requires a mold that is durable, easy to work with, and often times created from the same composites as the final part (for thermal expansion problems). The plug-mold method will produce higher quality molds but at almost double the labor and time required. A high quality buck and a high quality mold must both be created before the final part may be produced.

Direct to mold production is more commonly used on prototype applications where the mold will be used only a few times. While the final surface quality of the mold may be as good as plug-mold production, the mold is usually not as durable. This process, however, is much faster and may be cheaper in some instances.

For the team we have always used direct to mold to produce our shells. This is because the labor and materials required are lower than plug-mold production. Also, much less time is spent finishing and prepping mold surfaces. The team can do this only because we require one or two finished parts to be pulled from the molds.

Mold Foam

In order to create a direct mold a suitable material is required to machine in. Common mold materials include wood, metal, and high-density foam. Wood is commonly used on small prototype molds. Wood is not particularly stable and generally does not come in large enough volumes to produce our shell molds. Metal is commonly used in high production molds. Again, the size of metal molds is limited by the size of the initial ingot. Also, the cost of a car sized metal mold would be extremely cost prohibitive in materials and machine time. Foam, therefore, has become an extremely common

material to create molds. It is available in a wide range of sizes, densities, and chemistries. It is also dimensionally stable and is quite readily machined.

There are three common foams that may be considered for mold production; polystyrene, polyisocyanurate, and polyurethane. Polystyrene is the general-purpose foam sold at home improvement stores. Although extremely cheap it is easily destroyed by most solvents including gasoline, MEK, and many glues (specifically polyester resin and bondo). Polyester resin, therefore, requires epoxy resin to be glued together. Also, polystyrene machines poorly as heat from the mill bit can melt the surface of the foam as it machines along.

Polyisocyanurate foam, or trymer as it is commonly known, is a low to medium density foam used extensively in the marine industry. It is resistant to most solvents and can therefore be used in conjunction with polyester resin and bondo. Trymer, however, is easily marred and sheds foam when rubbed against. The main benefits of trymer are its good machinability and relatively low price.

Polyurethane foam is a medium to high-density foam used in general tooling operations. It is resistant to most solvents and can therefore be used in conjunction with polyester resin and bondo. Urethane is very stable and does not shed or chip as trymer does. Also, polyurethane is available in higher densities than either polystyrene or polyisocyanurate. This allows polyurethane to have a higher machinability and surface quality than polystyrene or trymer. The main drawback of polyurethane is its relatively high price. Table 1 compares all three foams.

Table 1: Foam Comparison Chart

Foam Type	Resin Compatibility			Machining	Durability	Density [lbm/ft ³]	Price [\$/ft ³]
	Polyester	Epoxy	Urethane				
Polystyrene	No	Yes	?	Poor	Poor	1-10	\$4.00
Polyisocyanurate	Yes	Yes	?	Good	Poor	2-6	\$7.00
Polyurethane	Yes	Yes	Yes	Excellent	Good	5-50	\$50.00

For the team's needs polyurethane is the best fit between the three foams. It is very stable and resists attacks by most common solvents. It is also easily machined and produces the best surface finish between the three foams. In addition to that, the team has successfully secured a continued sponsorship from General Plastics to supply polyurethane foam. For Borealis 3 General Plastics supplied the team with roughly 500 ft³ of foam valued on the order of \$25,000. The foam was given free of charge although the team had to pay \$xxx for shipping. The mold foam was shipped directly to PaR Systems and was received July 2, 2004.

Foam Layout

After foam is received it is necessary to design a foam layout for each mold. The foam layout should provide enough room to machine part, use an economical amount of foam, be easy to assemble, and easily mated to a supporting structure.

In order to leave enough room for machining and to allow for dimensional inaccuracies at least 3" of foam must be present between any surface of the finished mold and the outside of the initial foam block. A dimensional tolerance of roughly ± 1 " should be assumed when designing and assembling the molds. Also, there should be enough foam to allow for a parting flange roughly 6" wide along the entire perimeter of the part. This width allows enough room for composite overhang during the layup and room to lay tacky tape for the vacuum bag.

It is also important to minimize the volume of foam used on each mold. The mold foam is quite expensive and needs to be used for other parts as well as the body molds (fairings, canopy, etc.). The most inefficient initial block for a solar car is a rectangle encompassing all six sides of the respective shell. Any foam above the surface will be machined away and turns into foam dust on the floor of the machine shop. Any foam below the surface is simply there to hold up the foam above it. For Borealis 3 we tried to save as much foam as possible while keeping the time required to assemble the molds at a minimum.



Figure 6: Foam Assembly onto Mold Bases at PaR

A situation to avoid when laying out the foam is having continuous vertical seams running from the bottom to the top of the mold. These vertical seams, even when glued, can open up when the mold is stressed and lead to cracks in the mold surface. On Borealis II we had many problems with this and had to tape over a few cracks in the model just prior to the shell layup.

In order to save as much foam as possible we opted to cut down many of the foam blocks. We also chamfered quite a few blocks to give us the required joining angle between the front and rear sections of the top mold. The foam does not hot wire cut (it is much too dense) and is extremely hard to cut all the way through with a hand saw. On Borealis II a chain saw was used to cut most of the blocks, but this left a jagged surface with deviations as high as 1". We found that using a circular saw to cut through 4" on each side of the foam, then joining the cuts using a wood saw worked quite well.

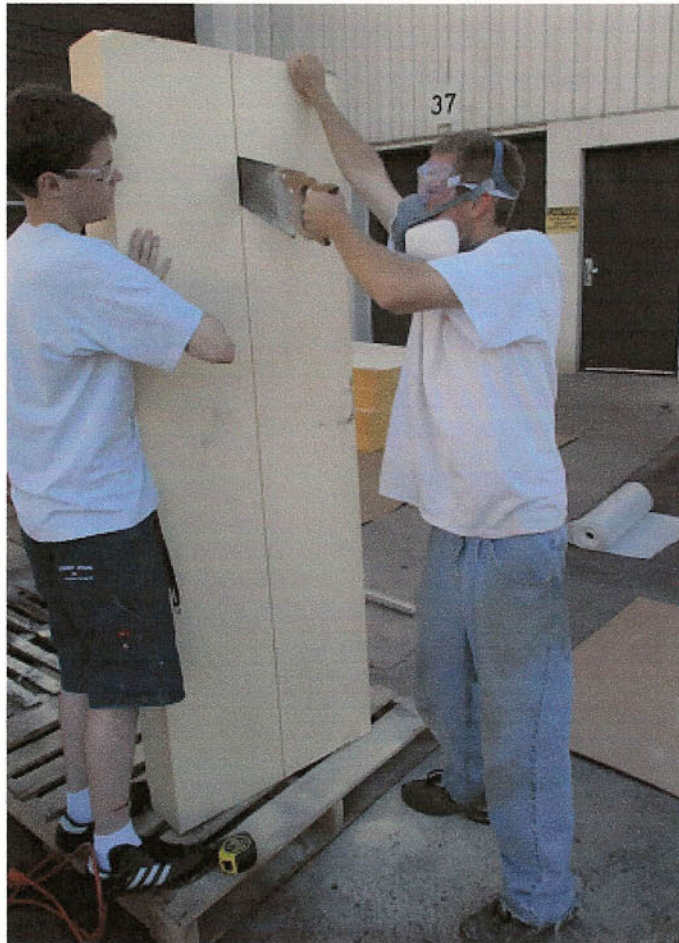


Figure 7: Finish Cutting of Foam Block after Circular Sawing

One problem found when assembling the foam for Borealis 3 was that the foam blocks were not perfect rectangles. Some of the blocks were bowed in the middle; as much as 1" over an 80" long block. These bows were not discovered until after we had machined the molds. The bows created internal cavities in the mold and this lead to a few 1" wide gaps between blocks on the final surface.

Mold Base

In order to transport the molds and to support them during machining and shell production mold bases are required. The mold bases are required to support all 2000 lbm of foam on each mold base while proving to be as stiff as possible.

Each mold bases was constructed from seven 14" Tall by 18' Long I-Joists. These joists were sheathed on each side with 15/32" CDX Plywood. When finished the mold bases measured 15" x 83" x 216". The width of the mold bases was designed to fit in the team's trailer with 1/2" on either side of the trailer's wheel wells.

Each mold base included four swivel casters spaced roughly 12' apart on a 6' center. The castors were placed so as to allow transportation in the trailer. The angle of the trailer ramp was calculated and used to determine how far in from the end the castor wheels could be located. The castors were made completely from steel and were 5" in diameter. Although they worked these castors proved to be extremely difficult to move and jammed up on numerous occasions. Larger castors with a plastic coated wheel should be used in the future. In addition we screwed four eye hooks onto the bottom of the mold bases to facilitate tying the molds down while being transported in the trailer.



Figure 8: Borealis 3 Top Mold after Framing

After we had finished machining of the foam we cleaned up the sides of the mold foam with the mill. We cut the sides of the base down planer with the side of the mold base. This allowed us to screw on 2" x 4" bumpers onto the molds to protect the foam from being sheared off of the surface of the mold bases. This saved the molds many times from damage during transportation.

Mold Machining

Logistics

In the Minnesota area there are only two known companies who have the capability to machine a full size shell mold in one part. A minimum machining work envelope of 8' x 18' x 2' is required to machine an ISF 5000 car. In addition the machine must be able to

handle jiggling and fixturing of a 2000 lbm part. The two companies in the area that have these capabilities are Remmele Engineering Inc. and PaR Systems Inc. Luckily for the team both of these companies sponsor the project.

Remmele is located in New Brighton, MN and specializes in complicated machining procedures. They are recognized as one of the leading aerospace machining contractors in the US. The Borealis 1 and Borealis II shell molds were both machined at Remmele. Remmele has permanent facilities to machine molds. Their schedule, however, can be full. Therefore early communication with Remmele is important to get into their machining queue. In addition lead times of a month or two should be expected from delivery of the completed mold bases to finished machining.

PaR Systems is located in Arden Hills, MN and specializes in designing and building advanced robot systems. One of PaR's business sectors includes large size milling for the marine and aerospace markets. The Aurora 2, 3, and 4 molds were machined at PaR as well as the Borealis 3 molds. Since PaR is a manufacturer of 5-axis mills it does not always keep one on hand. They are continually built and sold to customers around the world. Therefore there are periods of time where PaR will not have a mill capable of milling the shells. These stretches of time can vary from a few months to a year or more.



Figure 9: Borealis 3 Top Mold Rough Machining at PaR Systems

It has been the experience of the team that the molds produced from either sponsor are of high quality and accurate to the original design. PaR Systems, however, seems to take more time in surface finish which can save the team dozens of hours painting and sanding.

Time Required

The time required to machine a mold is dependant on many variables but generally revolves around how much work the team has done for the machinist before hand and the complexity of the part. Before designing a mold or mold base the team should talk with their sponsor and see what they would like to see in the mold. Also, the team should communicate what type of finished product they are looking to see. The machined surface finish and overall tolerancing of the shell should be decided before milling begins.

Generally speaking, with a smooth operation, a mold can be fully machined in two to three business days. One day is spent rough cutting, one day is spent finish cutting, and another day is spent on final clean up runs and datum cutting. While this is the actual machine time required, these days may drag into weeks and months if the sponsor's schedule is backed up.



Figure 10: Borealis 3 Top Shell Rough Cutting

Surface Quality

Surface quality of the machined surface is arguably the most important metric for solar car molds. Days or even weeks of manual labor can be saved if the machinist provides the team with a quality surface finish. For Borealis 3 we were able to get an exceptional surface quality on the final cutting. This allowed us to save tremendous time when it came time to seal the molds. For Borealis II the finished mold surface was much rougher. This led to a tremendous amount of time required to seal the molds.

The easiest entity to quantify in regards to surface finish is step over size. Step over is the distance between adjacent cutter tool paths. In order to cut the required part the mill follows lines created in the operator's computer. The distance between these lines is the step over size. Figures 11 and 12 show one half of the toolpath used on the bottom shell of Borealis 3.

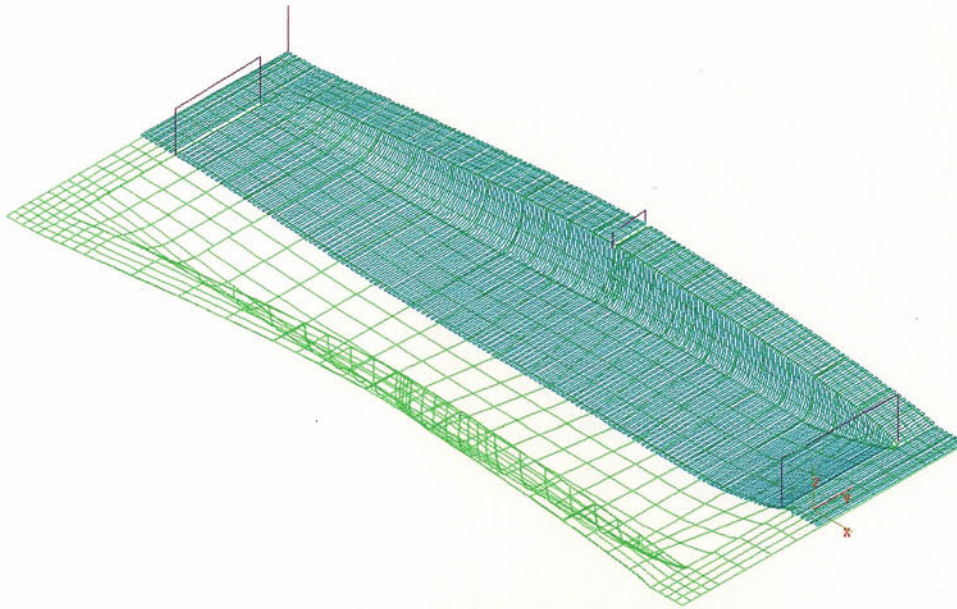


Figure 11: Borealis 3 Bottom Shell Toolpath

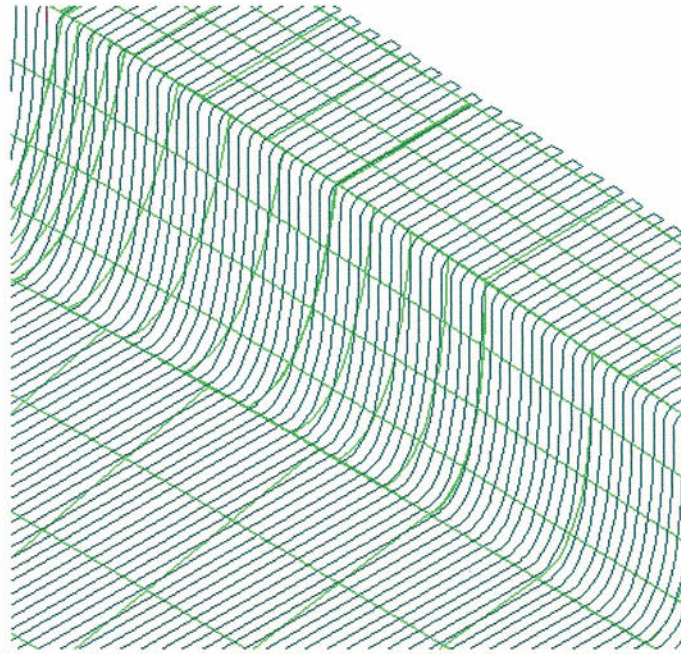


Figure 12: Borealis 3 Bottom Shell Toolpath Closeup

In most mold machining operations a large diameter ball end mill is used to cut the part. A ball end allows for concave features to be cut, as required by a female mold. The round end of the ball end mill creates tiny scallops that stick up above the ideal flat surface. The larger step over size between adjacent cuts, the higher and wider these scallops will be and vice versa. For Borealis II the step over size was roughly 0.250". For Borealis 3 the step over size was 0.063". Figure 13 shows roughly a full size comparison of the scallops produced by a 1" diameter ball end mill using a 0.250" and a 0.062" step over.

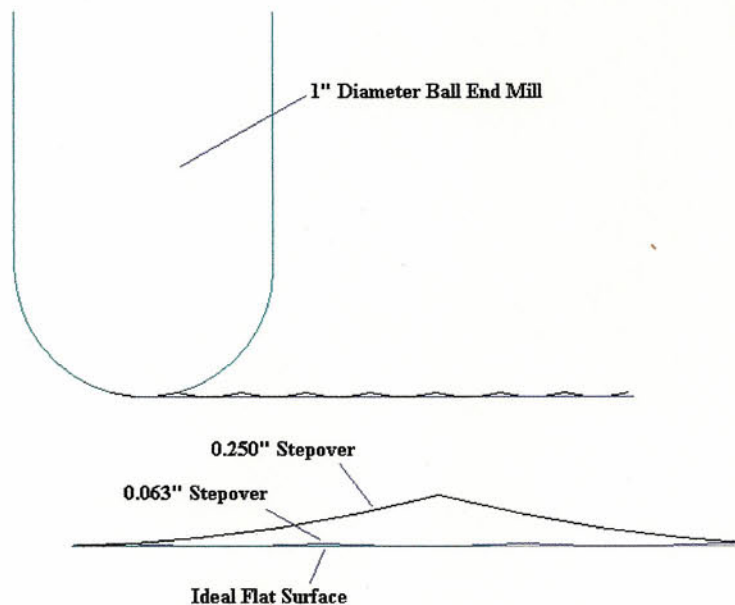


Figure 13: Step Over Comparison

As can be seen from the above figure step over size can have a dramatic impact on the time required to hand finish the molds. If large step over sizes are used large scallops will be present in the molds and these will require much hand sanding to bring them down to a flat surface.

Glue Seams

Another parameter that has an impact on surface quality is the size, location, and type of glue seam between the foam blocks that make up the molds. Any junction between two foam blocks will show up in the machined surface. The larger the gap the more work that will be required to smooth and fair out this juncture. When gluing up the foam blocks it is very important to try and make each glue seam as small as is practical. Any gap larger than about .250" will require a fair amount of time to repair. Also if glue seams are tangent or almost tangent to the final surface they will become very pronounced on the finish surface. This occurred on Borealis 3 towards the rear of the car on the top shell.

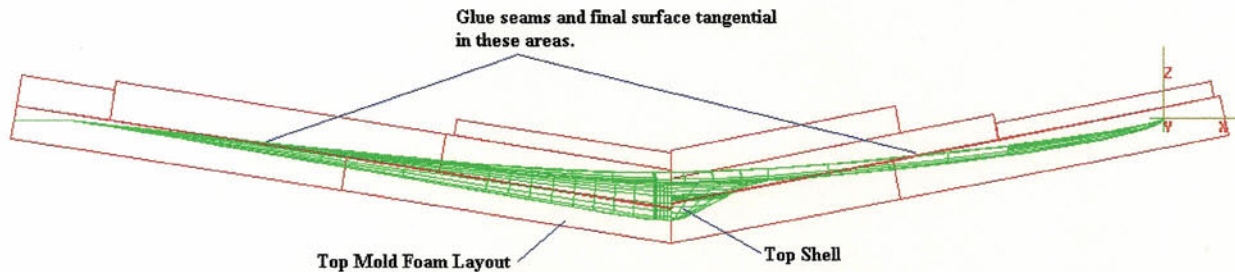


Figure 14: Borealis 3 Tangential Seams, Side View

These tangential seams took quite a bit of work to fair out and were quite a pain. When designing the foam layout for the car it may be advantageous to avoid tangential glue seams.

Foam Density

In addition to the machining quality and mold assembly, the density of the foam itself plays a major role in the surface quality. As a general rule the higher the density the smoother the surface finish will be. Also, higher densities of foam are less vulnerable to dents and scratches caused by mishandling. For Borealis 3 General Plastics supplied the team with 10 and 12 lbm/ft³ foam. In previous years the team received 8 lbm/ft³ density foam. Figure 15 and table 2 show how to read a General Plastics foam block part number.

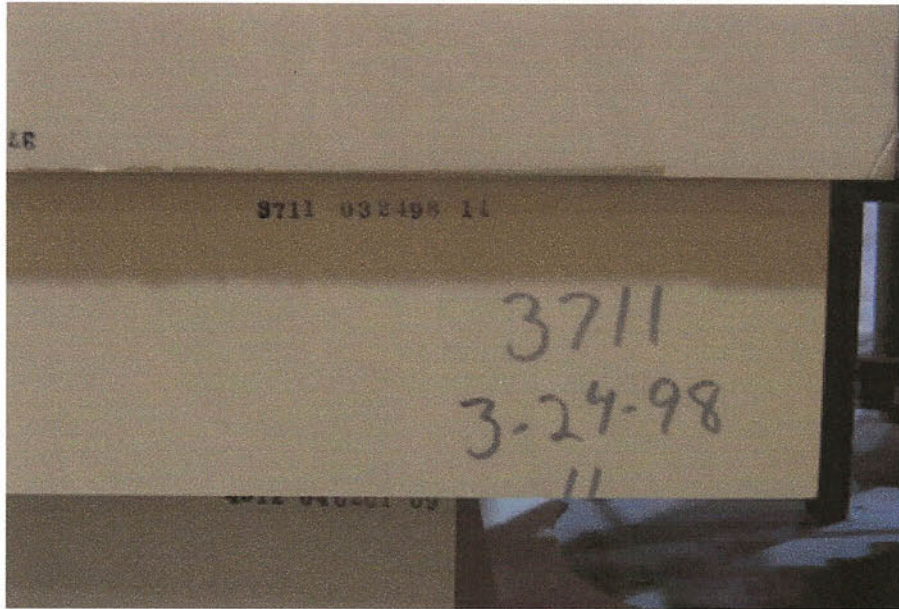


Figure 15: Mold Foam Serial Number

Figure 15 presents the Rosetta Stone of General Plastics mold foam. The serial number may be read as indicated in table 2.

Table 2: Mold Foam Serial Number Reader

37	11	03	24	98	11
Foam Type	Foam Density [lbm/ft ³]	Month Code [1-12]	Day Code [1-31]	Year Code [19XX-20 XX]	Foam Density [lbm/ft ³]

Mold Finishing

After the foam molds have been machined they require sealing to smooth them out and to prepare the surface for the layup. The mold finishing process is one of the messiest and most labor-intensive activities that the team completes. It is recommended that all the painting, filling, and sanding take place in a well-ventilated area. For Borealis 3 we were extremely lucky in that we were able to use PaR's full size paint booth for the entire finishing process.

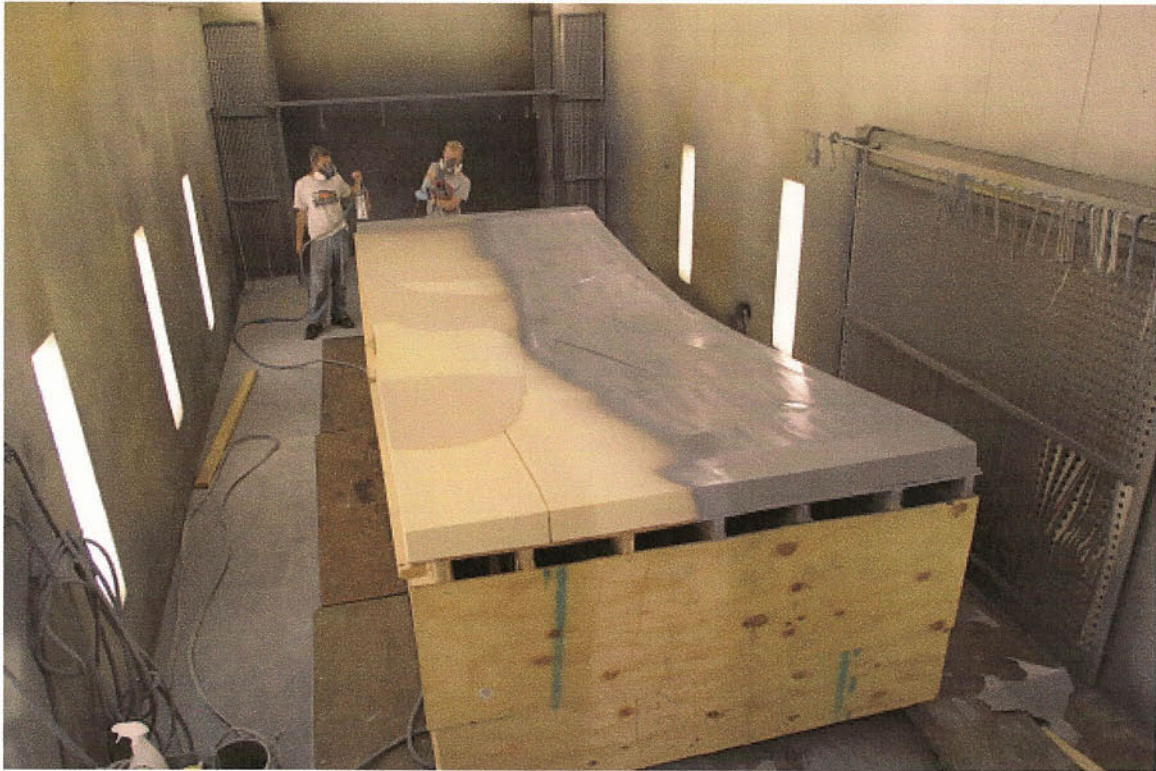


Figure 16: Borealis 3 Top Mold's First Coat of Primer in PaR's Paintbooth

Painting

The purpose of the paint is to seal the surface of the mold and to smooth out any small bumps that still may exist after machining. General Plastics recommends a high build automotive primer to be used on their foam. The team has had much success with DuPont's Uroprimer urethane primer. Uroprimer is readily sprayed, easy to sand, and does an excellent job of filling small nicks and cracks in the mold surface. The primer is applied in three or four coats in alternating colors. Alternating colors are used to indicate, while sanding, when one layer has been completely sanded through into another. This indicates how much material has been removed with each sanding session and can highlight problem areas of the mold.

Filling

While the primer may fill small irregularities large fissures and problem areas will need to be addressed with an auto body filler (aka Bondo). Automotive fillers are polyester based so they smell strongly and have a work life of about 15 minutes. Also, bondo may be sanding on 20-30 minutes after application. A high quality bondo should be used that is easily sanded. The team has used 3M's "Gold" and "Lightweight" series fillers with great results. When applying bondo it is extremely important that only small amounts are used to fill cracks and divots. Large domes or mounds should not be applied and then sanded down later. This will cause the foam around the large mound to be sanded away as the bondo is much harder than the foam. Apply only enough bondo to just barely fill

the hole. If need be do not be afraid to build up cautiously in two or three sessions to avoid over applying the filler.

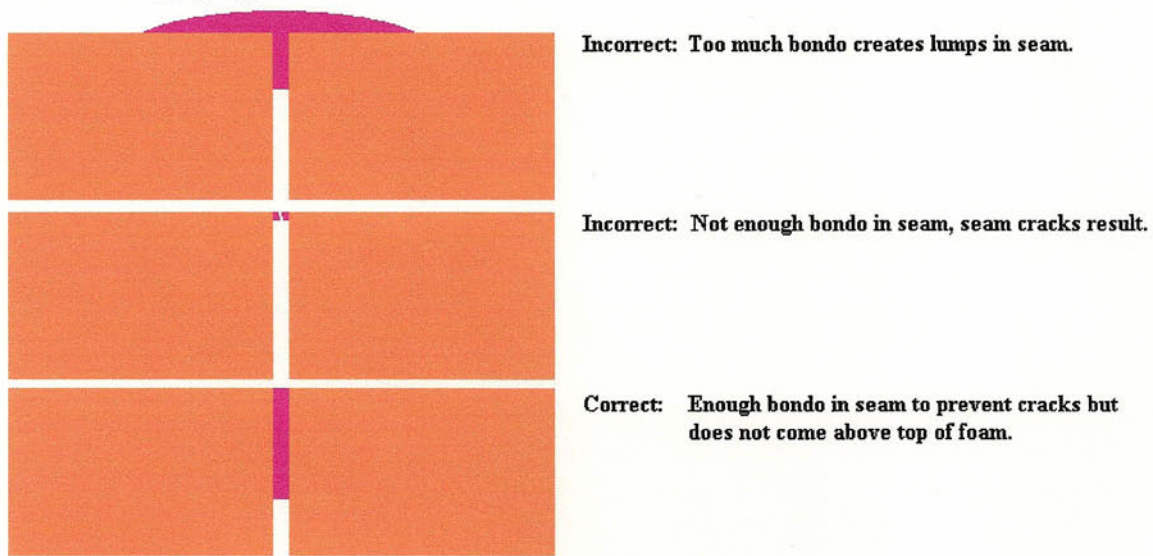


Figure 17: Seam Filling

Sanding

Sanding is used to even out the surface of the mold and to smooth out any irregularities. It should be assumed that the machined surface of the mold is as accurate as possible, so sanding into the mold foam should be avoided in almost all instances. For sanding between coats of primer 180 grit sandpaper works well. For finish sanding of the mold 400 grit dry and then 400 grit wet sanding produced a very smooth surface for Borealis 3.

Back Filling

For areas where large gaps are present between the foam back filling may be required. Back filling requires that as much bondo or resin be crammed into the foam seam to provide structure for the built up top surface. The more material that can be jammed down into fissures that better as this will help tie together the mold and assure that hairline cracks do not form later. On Borealis II we had many small seam cracks that kept reappearing because the glue seams they were located on top of were not filled with enough bondo. Transporting the molds tends to flex the mold bases and help open up seams that were not filled adequately. On Borealis 3 we tried as hard as possible to fill each gap with as much bondo as possible.

Finishing Sequence

The previous four steps of painting, sanding, filling, and back filling need to be followed in a specific order to achieve good results. Above all it is extremely important that an initial coat of paint should be laid down before any other operation is performed. For Borealis 3 we followed the procedure in table 3 with much success.

Table 3: Mold Finishing Sequence

Procedure	Comments	Material	Time [hr]
1st Coat of Paint	Heavy Coat, Grey	Uroprimer	4
Paint Dry		NA	12
Back Fill	Structurally Re-enforce Joints	Bondo, Polyester Resin	4
2nd Coat of Paint	Medium Coat, Tan	Uroprimer	3
Paint Dry		NA	12
Fill	Filled Seams and Machining Marks	Bondo	2
Sand	Largest Amount of Sanding	180 Grit Dry	8
3rd Coat of Paint	Light Coat, Grey	Uroprimer	3
Paint Dry		NA	12
Sand		180 Grit Dry	5
Sand		400 Grit Dry	2
Sand	Final Wet Sand	400 Grit Wet	2



Figure 18: Borealis 3 Top and Bottom Molds after Machining

Appendix

Contact List

3M

Kelli M. Novak
Community Affairs
kmmnovak@mmm.com
Work: 651-733-1760
Fax: 651-737-3061

3M provided the team with polyester resin, bondo, sandpaper, and respirators.

Team Contact: Dr. Starr and Al Majkrzak

Advanced Composites Group

David Young
dyoung@prepregs.com
860-564-7817

Advanced Composites Group provided the team with a 40" x 32 yard roll of 1.8 oz/sq. yard kevlar prepreg. This was used on the top shell.

Team Contact: Al Majkrzak

Boeing

william.m.sheridan@boeing.com
gerald.n.roe@boeing.com
james.a.carris@boeing.com

Boeing provided the team with two rolls of carbon fiber prepreg for Borealis 3.

Team Contact: Aaron Westman

DuPont

Rick Langlie
Performance Coatings
6015 Manchester Trafficway
Kansas City, MO 64130
Work: 763-458-3810
Cell: 763-458-3810

Team Contact: Dr. Starr

General Plastics

Bob Rezba
Tacoma, WA
www.generalplastics.com

General Plastics provided all of the polyurethane foam used to produce the molds.

Team Contact: Dr. Starr

Lowells Paint

Tim Zitzloff
Work: 952-392-6084
Cell: 612-760-5776

Lowells Paint supplied the team with DuPont Uroprimer that was used to seal the molds.

Team Contact: Dr. Starr and Aaron Westman

Northwest Airlines Composite Shop

Ray Kaiser
ray.kaiser@nwa.com
7500 Airline Blvd
Dept C8535
Minneapolis MN 55450

Northwest Airlines allowed the team to layup both shells in their lab. They also donated vacuum bagging and other layup materials.

Team Contact: Aaron Westman

PaR Systems, Inc.

Charles Habermann
Applications Engineer
899 West Highway 96
Shoreview, Minnesota 55126
chabermann@par.com
Work: 651-528-5209
www.par.com

PaR Systems provided the team with construction and storage space for the mold bases and foam. The General Plastics shipment was sent directly to PaR's facility in Shoreview. PaR also machined both molds on their 5-axis mill. In addition PaR allowed the team to use their paint booth to paint, prep, and sand both molds.

Team Contact: Dr. Starr and Al Majkrzak

Plascore, Inc.

Luke Young
Sales & Marketing
Luke.Young@Plascore.com

Work: 616-748-2229
Fax: 616-772-1289
www.plascore.com

Plascore provided the team with the core used in the shell layups. The core was sold to the team at cost.

Team Contact: Al Majkrzak

Remmele Engineering Inc.

Steve Parmenter
Work: 651-635-0149
www.remmele.com

Remmele machined the previous car's molds (Borealis II) during the fall of 2002.

Team Contact: Al Majkrzak

Shaw/Stewart Lumber Company

645 Johnson St. NE
Minneapolis, MN 55413
612-378-1520

Shaw/Stewart provided the team with lumber at cost to produce the mold bases.

Team Contact: Aaron Westman

General Plastics Foam Inventory

Qty	Length [in]	Width [in]	Thickness [in]	Volume [ft^3]	Total Volume [ft^3]
4	72	26	6	6.5	26.0
4	60	21	6	4.4	17.5
4	48	48	6	8.0	32.0
1	80	42	5	9.7	9.7
2	80	42	7	13.6	27.2
1	83	42	4.5	9.1	9.1
4	83	42	8	16.1	64.6
16	48	24	8.5	5.7	90.7
2	47	47	5.5	7.0	14.1
1	81	41.5	5.5	10.7	10.7
1	81	41.5	7	13.6	13.6
1	81	41.5	8	15.6	15.6
1	82	60	4.5	12.8	12.8
2	82	60	7	19.9	39.9
4	48	46	6	7.7	30.7
4	74	26	6	6.7	26.7
4	60	21	6	4.4	17.5
16	31.5	39.5	3	2.2	34.6
				Total	492.8

Wood and Hardware BOM

Qty	Unit	Description	Supplier	Unit Price	Group Price
14	Unit	14" Tall X 18' Long I-Joist	Shaw/Stewart	\$47.52	\$665.28
20	Unit	4' X 8' - 15/32" CDX Plywood	Shaw/Stewart	\$18.24	\$364.80
32	Unit	2" X 4" - 10'	Shaw/Stewart	\$4.53	\$145.06
	Tube	Liquid Nails	Home Depot		\$0.00
4		Deck Screws	Home Depot		\$0.00
8	Unit	5" Steel Caster	Northern Supply		\$0.00
12	Gallon	Fiberglass Resin 05834	3M	\$0.00	\$0.00
1	Gallon	Premium Body Filler Gold QBA 05835	3M	\$0.00	\$0.00
1	Gallon	Lightweight Body Filler 05801	3M	\$0.00	\$0.00
		Filler	Lowells Paint	\$0.00	\$0.00
		Thinner	Lowells Paint	\$0.00	\$0.00
		Accelerator	Lowells Paint		

Solar Miner IV Body

This paper was written by Eric Pieper, a member of the 2003 Rolla team. The paper was posted online at <http://www.opencortex.com/cn00000349>. It details the construction procedure for the body of Solar Miner IV. It has been included to present an alternative solution to the problem of producing a composite solar vehicle shell. In almost every regard Rolla's construction philosophy differs from Minnesota's. Instead of an expensive mold they employ a procedure called the "Rutan Method". A wooden buck comprised of plywood stations controls the shape of the car. Although cheap, the quality of the final product produced can be less than spectacular. It takes great skill to pull off a quality shell with this method. In 2003 Rolla successfully produced one of the lightest shells in the field with some of the fewest resources. There is something to be learned by their words.

Solar Miner IV Body

by Eric Pieper

solarpieper@yahoo.com

created 8/4/2003

submitted 9/15/2003 06:37:09 PM

This is a short paper about some of the processes used to manufacture the body of Solar Miner IV.

SMIV BODY

Design-

I have only a basic knowledge of aerodynamics so I wasn't involved much in the aerodynamic design of the body for Solar Miner IV. I was, however, involved in the fine tuning of the shape to allow for optimum array power and also to allow the chassis and suspensions to not hit.

For the array optimization the UniGraphics model of the body, sans the nose, was divided into the same number of points as we had solar cells. The three dimensional coordinates of the points were then given to the EE's. From the points it was determined what angle the cells would be pointed while driving down the road. This information was then plugged into a program that would give the optimum sub-array configuration. From this data, and the efficiency of the solar cells, we were able to get a rough estimate of how much power we would receive from the sun. Several iterations of this were done until the body shape was changed as much as we dared.

Now we tried to fit the chassis and the suspensions under the body only to find that the front suspensions would go through the body at maximum bump. To remedy this situation the suspension mounting points were adjusted as well as the body shape being changed slightly. After many heated discussions it was finally determined exactly how much each of the two would be tweaked.

With the shape of the body now determined a nose of a pre-determined length was added to the drawings. When it appeared that all of the components mated together smoothly we finally called a halt to the designing and sent the designs to the production team.

Once the finalized design was received, Casey Schultz and I determined the spacing we would use for the mold ribs, as well as the internal ribs. For the mold rib spacing we chose 20" (I think) and for the internal ribs we used the same configuration as on Solar Miner III. Looking back we should have reworked them to space the wheels in the middle of the wheel wells.

With the spacing of the ribs decided, we divided the drawing at the places the mold ribs would be. We transferred the outputs of the points to splines in AutoCAD. The splines were then transferred onto a mold rib template with a fixed origin. The rib drawings were then transferred to the waterjet software.

Mold Manufacturing-

With the drawings complete we cut the ribs from 1/4" plywood. Because of the size of the ribs, each one had to be divided in half for the waterjet to be able to handle it. These halves were then attached together with scraps of plywood. A 2 X 4 frame for the mold was built and the diagonals measured to ensure it was square. The form was then braced at all four corners with large triangles of plywood. Next, small pieces of 2 X 4 were screwed to each end of all the ribs. These pieces of 2 X 4 were then screwed to the form. We made sure the ribs stayed aligned by running 1/2" conduit piping through guide holes in each rib.

Now we had to make the mold ready to build the body. The top of each mold rib was felt for any imperfections. If anything was found it was then fixed with glass bubbles and/or sandpaper. Originally a small "shelf" was made on both sides of the body, marking the point where the side rib would go. For the good body these were removed because they proved to be a pain. One suggestion I have is to make an apparatus that will attach to the mold ribs and hold the internal ribs of the body in place while they are drying.

Body Manufacturing-

With the mold ready, we went about the task of laying down the top of the body. For this a very thick mixture of glass bubbles was made. It was about the consistency of peanut butter. The glass bubbles were dabbed onto the mold rib at various spots. Full sheets of 1/2" blue Styrofoam were pressed into the mold and glued together in the middle with a thinner glass bubble mixture. I have still not found a really good method for getting the edges of all four sheets to match up wonderfully in the middle. One method that had mild success was to overlap the sheets and then cut through both of them at once. The big problem with this method was cutting a straight line. When we made the good body for SMIV we attached the rear two sheets of the body first, weighted them down, and allowed them to dry. We then repeated this with the front two sheets. We kept the sandbags on the foam to ensure that it wouldn't try to pull away from the mold even after the glass bubble was dry.

Since the internal ribs were already designed, all we had left to do was draw triangular shaped holes in them and send the drawings to the waterjet. For the inner lengthwise ribs and the front crosswise ribs we laminated Kevlar to a couple of sheets of Styrofoam. MAKE SURE YOU REMOVE THE PLASTIC FROM THE FOAM!!

While the ribs were being cut we laid up the inside of the body with Kevlar. The Kevlar was laid at a 45 degree bias for extra strength. The epoxy was spread onto the Kevlar from the center out. This method helps to minimize the amount of wrinkling that occurs. If there are any wrinkles in the fabric they must be worked out before it dries. Even a small wrinkle can cause delamination down the road. The pieces of Kevlar should overlap approximately 2 inches. The Kevlar should be sufficiently wetted, but should not have any pools of epoxy on it.

When the ribs arrived from the waterjet we had to do some assembly on them. Since the cutting area of the waterjet could only handle a small amount of the large ribs we had to break them into four sections. Each section had a unique pattern at the end of it so that it would only fit where it was supposed to. First we glued the pieces together with glass bubbles. Then we laid scraps of Kevlar over the seams for extra support. With the ribs all attached together we added them to the inside of the body. Pushpins were used to hold the ribs in place and sandbags were used to weight them down. A specially designed jig here would have helped greatly in keeping the ribs from being wavy. After the glue holding the ribs was dry we went back and ran a small radius of glass bubbles along the seam between the body and the ribs.

With the ribs all in their proper places we began attaching the bottom of the body. We used one sheet of foam across the back, one up either side, and one across the front. This ended up being wrong and we had to add more to the back later. It would have been easier to do it all at once. Before we glued down the foam we made sure that all of the proper wires had been ran in the body. We realized that after attaching the bottom it would be almost impossible to run them. When it was time to start, glass bubbles were added to all of the ribs and along the back of the body. The sheets of foam were then laid down and weighted down with sandbags on top of all the glued points.

Nose-

For the nose of the body we determined a distance over which we would like to try and perfect surface smoothness. I think we chose somewhere around 18 inches. The thing that made the nose different from the rest of the body was that when looking down from the top the edges were rounded. To make the shape of the nose we fit a curve around the front of the car to as far as we were willing to go without sacrificing too much array area. Once completed, we divided the drawing into sections, each $\frac{1}{2}$ " thick. When the drawings were all worked out we had the pieces water jetted out of $\frac{1}{2}$ " foam. $\frac{1}{4}$ " guidance holes were made along the middle so the pieces would align properly after being cut.

After we got the pieces back from the waterjet, we glued them together and placed 1/4" dowels through the guide holes. It is important to remember that even if you have several dowels holding the pieces in place, it is still possible for them to shift. Something needs to be done to hold the dowels at right angles to the bottom piece. When the nose was dry we began to sand the outer shape. A mistake we made was to begin sanding before we had glued the right and left halves of the nose together. This made for uneven curvature of the nose. After the outer shape was complete we hollowed out the inside of the nose. We left around 3/8" of foam around the entire piece except for what would be the very front of the car. We left a little more at this point because we would have to attach the turn signals here. Next we put a rib into each half of the nose.

Before we could attach the nose to the body the exact position of the turn signals had to be determined so the wires could be run. To run the wires we drilled holes through the nose. To attach the LEDs we hollowed out a little hole just big enough for the light. We then glued the light into place with glass bubbles.

To attach the nose to the body we sharpened two of the 1/4" dowel rods and made a couple of alignment holes in the front rib of the body. We then aligned the nose with these holes and used glass bubbles around the edges to secure it to the body. We used ratchet straps along the length of the body to hold the nose in place while it dried.

Tail-

For the tail of the car we used a sheet of 1/2" foam and cut it to the proper dimensions to fit the rear of the car. Next we cut holes for the taillights and attached them in. Now the entire tail was glued to the car using glass bubbles. Once the tail was dried on the car we sanded it until it was curved sufficiently. Between Formula Sun 2003 and American Solar Challenge 2003 more of the tail had to be sanded off to meet length requirements. This made the taillights stick out a little.

Canopy-

For the canopy shape we filled in the roll bar of Solar Miner III with chunks of foam. Since the roll bars of SMIII and SMIV were very similar the size would be very close. The foam was then sanded to a shape that would fit closely around the roll bar and still be not un-aerodynamic. On this shape we sprayed a covering that would sand very smooth and could be sealed. We then applied about 14 coats of wax to this. Each coat of wax was allowed to dry before the next coat was added. Now we sprayed a layer of gelcoat to this. Once the gelcoat was dry enough we laid up scraps of fiberglass to it. We kept laying up fiberglass until we had between an eighth and a quarter inch of glass built up. When this was dry we took the mold off of the plug. The next step was to put about 14 coats of wax onto the gelcoat finish of the mold. The wax was applied in the same manner as the previous time. Once the waxing was finished the carbon fiber for the part was cut. For the final time we used two layers of carbon with the fibers running in opposite diagonals from how the part would be. When pulled out of the mold the part had a smooth outer

finish.

After the canopy was made we attached it to the body. We did this by setting the body onto the chassis, with the roll bar sticking through a hole in the body. We then cut the canopy to the proper size through several iterations. Once the size was definite, we placed it on the body and used glass bubbles to glue it down.

Next the windshield was made from plexiglass. The glass was cut to approximately the shape that would be needed. It was then put into an over to allow it to become soft. Once the glass was soft enough it was pulled out of the over and formed using the mold. Felt was placed between the mold and the plexiglass so nothing would get damaged. This process took us way too many tries for this car, but once you can get it right it will make an excellent windshield.

With the windshield and the canopy now done we went about attaching the two of them together. First the windshield was cut to the size we wanted it. Next a hole was cut into the canopy that the windshield would fit into. The windshield was then placed into the canopy from the inside and glued around the edges. After the glue was dry we went back and worked on the outside seam using aeropoxy light. Aeropoxy light was then used around the perimeter of the canopy as well. For the vent, a small hole was cut at the front of the canopy at the point where it meets the body.

Bellypan-

The shape of the bellypan was taken from the bottom of the body drawing. The bellypans for the previous cars were flat and this one was going to be curved. We decided that we were going to make the front of the bellypan from carbon fiber and use a sheet of foam for the back portion. We would accomplish this by having a solid mold in the front and only ribs toward the back of the mold. To make the bellypan mold we once again divided the drawing into sections. For the front we used about 21 pieces of 2" foam. For the back we spaced out ribs made from 2" foam. After the pieces were cut using the waterjet, we glued them together and sanded them smooth. A coat of thin glass bubbles was applied to try and seal all of the pores and cracks.

Now we were ready to begin the manufacturing of the part. For the front we were using two layers of carbon and a layer of Kevlar. For the rear it was a sheet of foam with Kevlar on both sides of it. We laid the first layer of carbon for the front and then we put the foam into it. With this done we proceeded to lay down the layer of Kevlar and the other layer of carbon. The initial plan was to vacuum bag all of this down. This didn't work though because we couldn't get a good vacuum on the whole surface due to the foam mold and the sheet of foam hanging out the back. In the end we piled everything we could on top of the solid mold to try and help the layers bond better. First we covered the surface with a couple layers of sandbags. Then we stacked on everything we could find that had weight to it. When the epoxy was dry we pulled everything off and got our first look at it. Although it wasn't near as nice as vacuum bagging would have made it, it wasn't too bad. With a little Aeropoxy light and some sanding it would be in good shape.

We now laid up the Kevlar onto the sheet of foam, while it was on the mold still. With the Kevlar still wet we used wax paper to place sandbags onto the foam/Kevlar, so it would conform to the mold. After it was pulled from the mold the front of the bellypan needed extra support so a couple of cross ribs were added.