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Development Effort on Sheet Molding Compound (SMC) Parabolic Trough Panels

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Contract No. 13-8720

Abstract

This report describes in detail the approach taken to develop integrally molded reflective glass with sheet molding compound into parabolic trough solar reflectors.

ACKNOWLEDGMENT

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1.0 INTRODUCTION

The Department of Energy, through Sandia Laboratories, is sponsoring development of parabolic trough solar collectors. Improvements are required in present state of the art optical/thermal performance, durability, and reliability prior to commitment to mass production. The Trough Development Project has as its goal the development and demonstration of trough collectors with potential for mass production with the incorporation of design features which have been indicated by previous collector development and testing.

Objectives

The objectives of the development effort are to:

- Investigate the problems of molding parabolic trough solar reflector panels of sheet molding compound (SMC)
- Develop molding techniques and processes by which silvered glass reflector sheets can be integrally molded into SMC trough panels
- Provide representative prototype panels for evaluation
- Provide information regarding the technical feasibility of molding SMC panels in high volume production.

The approach taken to meet the objectives was to design the parabolic panel, fabricate a prototype die, choose an SMC formulation and mold the glass and SMC together into a vertex to rim mirrored panel. The main thrust of the program was to successfully co-mold a mirrored glass sheet with the SMC, thus eliminating subsequent mirror to structure bonding operations and providing a good environmental seal for the silver coating on the molded surface of the glass. Co-molding of the mirror with the SMC also offers the potential for reducing the overall cost of SMC parabolic trough panels.

Results

Results have indicated that mirrored glass sheets, if properly strengthened to withstand the temperature and pressure of the molding process, can be successfully molded with SMC in a single press stroke using standard compression molding techniques. The silver reflective surface must be coated with an adhesive mixture that provides both protection of the silver and adhesion to the sheet molding compound. The SMC material must provide the strength and stiffness required of a structural backing material. Given these three parameters, that is, strengthened silvered glass, a protective-adhesive coating, and structural SMC, the actual molding of vertex to rim parabolic reflector panels has been successfully completed and presents no major problems to prototype molding. More detailed preparation would be required before production molding could become practical, but the technical feasibility of molding panels in high volume production has been established in this program.

2.0 TECHNICAL CONSIDERATIONS

2.1 PART DESIGN AND TOOLING CONSIDERATIONS

The panel design as required by Sandia was a vertex to rim parabolic trough reflector panel, one meter wide with a one square meter projected aperture area and a focal length of 19.01 inches. The structure of the panel was to be a sheet molding compound with specific requirements as outlined by Sandia. The part size was selected to be a vertex to rim panel with 1 m x 1 m aperature primarily because of tooling costs. A full rim to rim 1 m x 2 m panel could probably have been molded; however, the tooling would have been more than double the size, weight and depth of the tooling required for a half parabola. Figure 1 shows the tooling comparison. For development, the 1 m x 1 m half panels were adequate for establishing feasibility of co-molding strengthened glass mirrors into an SMC structure. Two basic designs were considered to provide the required stiffness of the panel under wind loading conditions. The first design would use separately molded and bonded hat section parts as the panel stiffening elements whereas the second design would use molded ribs for panel stiffening. Each design has advantages and disadvantages as outlined in Table 1. With an eye towards mass production, it was decided to use ribs as the stiffening elements. The final panel design is shown in Figure 2.

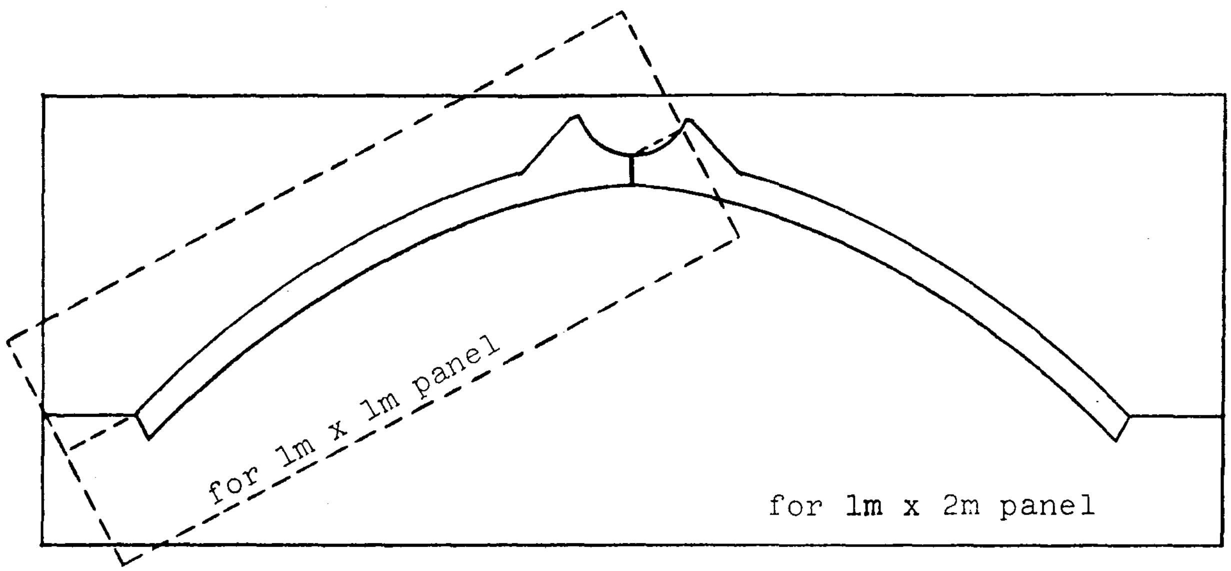


Figure 1. Tooling Comparison

TABLE 1 - Advantages and Disadvantages of Stiffeners

STIFFENER	ADVANTAGES	DISADVANTAGES
Hat Section	-Not as much part-to part consistency in the panel is required -Molding is better defined	-Cost of bonding operations in a production environment -Matching of different curvatures of SMC/ Glass panel vs. a plain SMC panel (because of thermal expansion difference) with a consistently curved hat section stiffener
Ribs	-Cost of a one-piece, ready to assemble panel	-Greater part-to part consistency in the panel is required -Possible read-through of ribs on glass surface -Practical problems of molding deep ribs

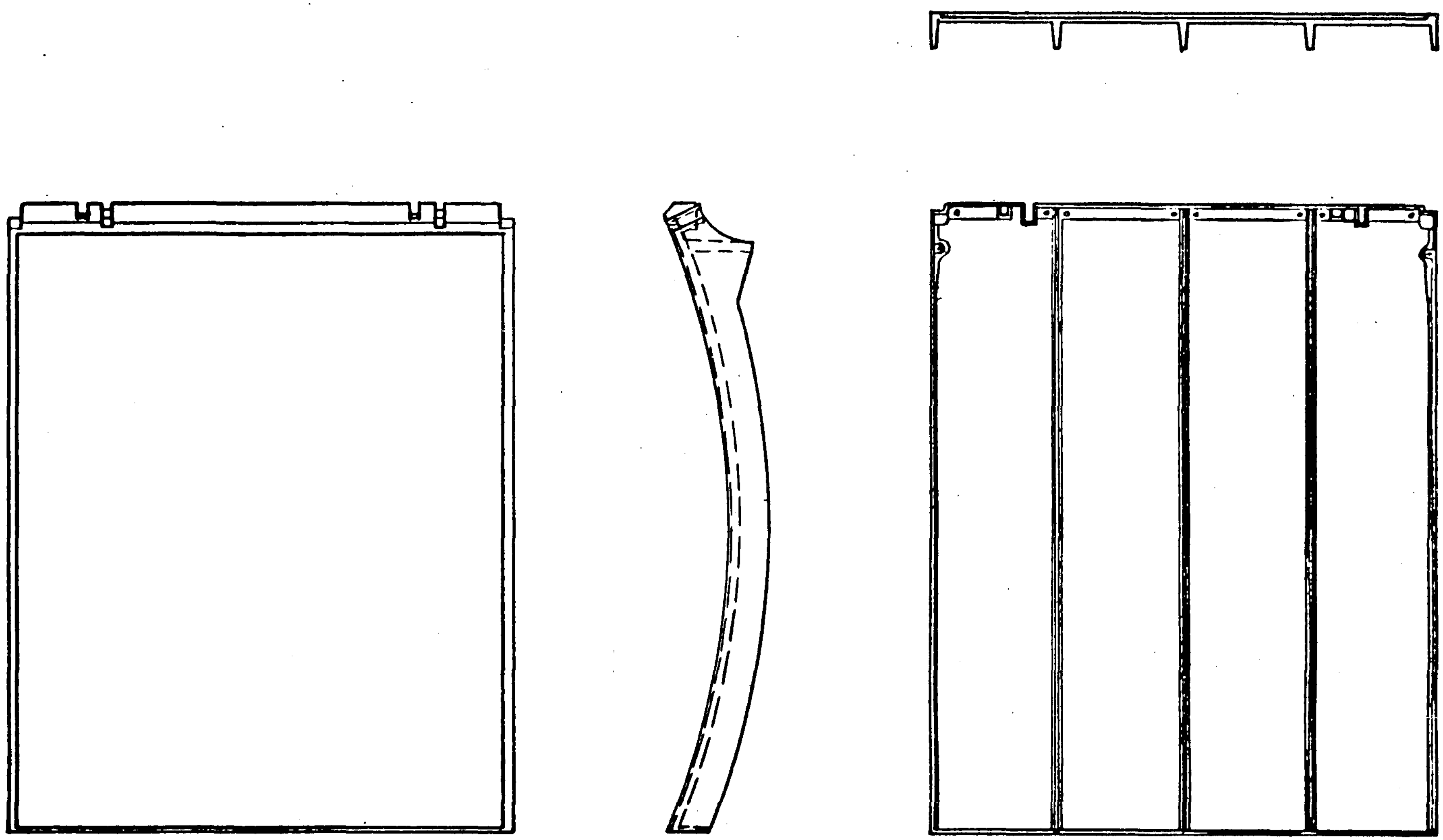


Figure 2. Final Panel Design

Three problems were presented in the detail design of the panel: rib geometry, location devices in the mold for glass positioning, and the thermal expansion coefficient difference between glass and SMC. The solution to each of these problems will be discussed. The rib geometry includes rib height, rib thickness, draft angle and fillet radii. The structural analysis performed by Sandia indicated that three internal ribs in conjunction with the two external coaming ribs would provide the required stiffness if the ribs were on the order of two inches in depth and 0.150 inches to 0.175 inches average thickness. The question arose as to the practicality of molding these ribs. From previous experience the draft angle for internal ribs should be approximately 1.5°. With a total panel depth of 2.25 inches, the rib height would be 2.05 inches. See Figure 3. The tip of the rib should be wide enough to allow glass fiber flow to that area and the root of the rib should not be so wide as to present problems with curing of the material or with sink marks. With these criteria, the tip thickness was determined to be 0.120 inch nominal and the root thickness 0.230 inch nominal. Another controlling factor in reducing sink marks, which are depressions opposite ribs and bosses caused by material shrinkage, is minimizing the lead-in radius to the rib. Although small radii may reduce sink they also may reduce fiber flow into the area. It was decided to make the lead-in radii at a minimum, approximately 0.010 to 0.020 inch, and determine the fiber flow into the rib after molding a few panels. If the fiber flow would need

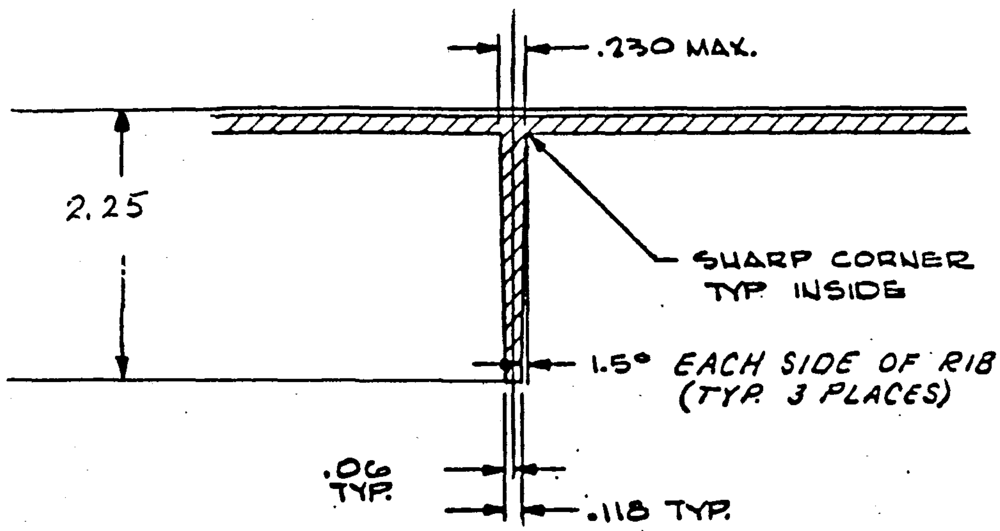


Figure 3. Typical Rib Cross-Section

to be increased, the radii could be increased by breaking the sharp corners on the rib side mold half and hand finish to the desired radius. Figure 4 shows the completed panel cross section.

Location devices for positioning of the glass sheet in the mold presented another design problem. Figure 5 shows an initial concept employing four gaging blocks, two each in opposite corners of the mold punch. On the downward stroke of the cavity the gaging blocks move down and become part of the punch while allowing the glass mirror to be placed in the proper position. This concept was not used because: 1) the edge of the glass could rub on the gaging blocks causing the glass to shatter; 2) the dimensional tolerance of the glass could be such as to make the gaging blocks non-workable; and 3) the cost of the gaging blocks for a prototype application was expected to be prohibitive. Another idea, Figure 6, would use premolded SMC parts that would hold the glass in position with the correct spacing. Once again, tolerance limitations and cost made this concept impractical.

It appeared that the glass sheet could be positioned in the die by making the angle of the vertex and rim coamings nearly vertical to prevent springback of the chemically strengthened glass to its original flat position. Vertical is defined as being parallel to the press movement. Vertical coaming on the rim side presented no problems because the function of the rim coaming is to end the panel. However, the vertex coaming angle relative to the press movement was critical when joining two panel halves and could only be changed in a position that would not influence the panel

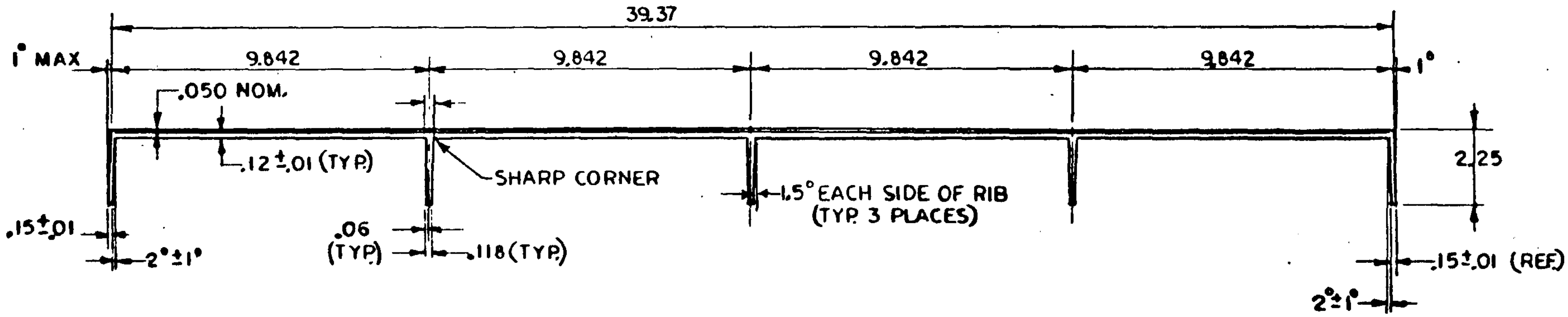


Figure 4 - Trough Panel Cross-Section

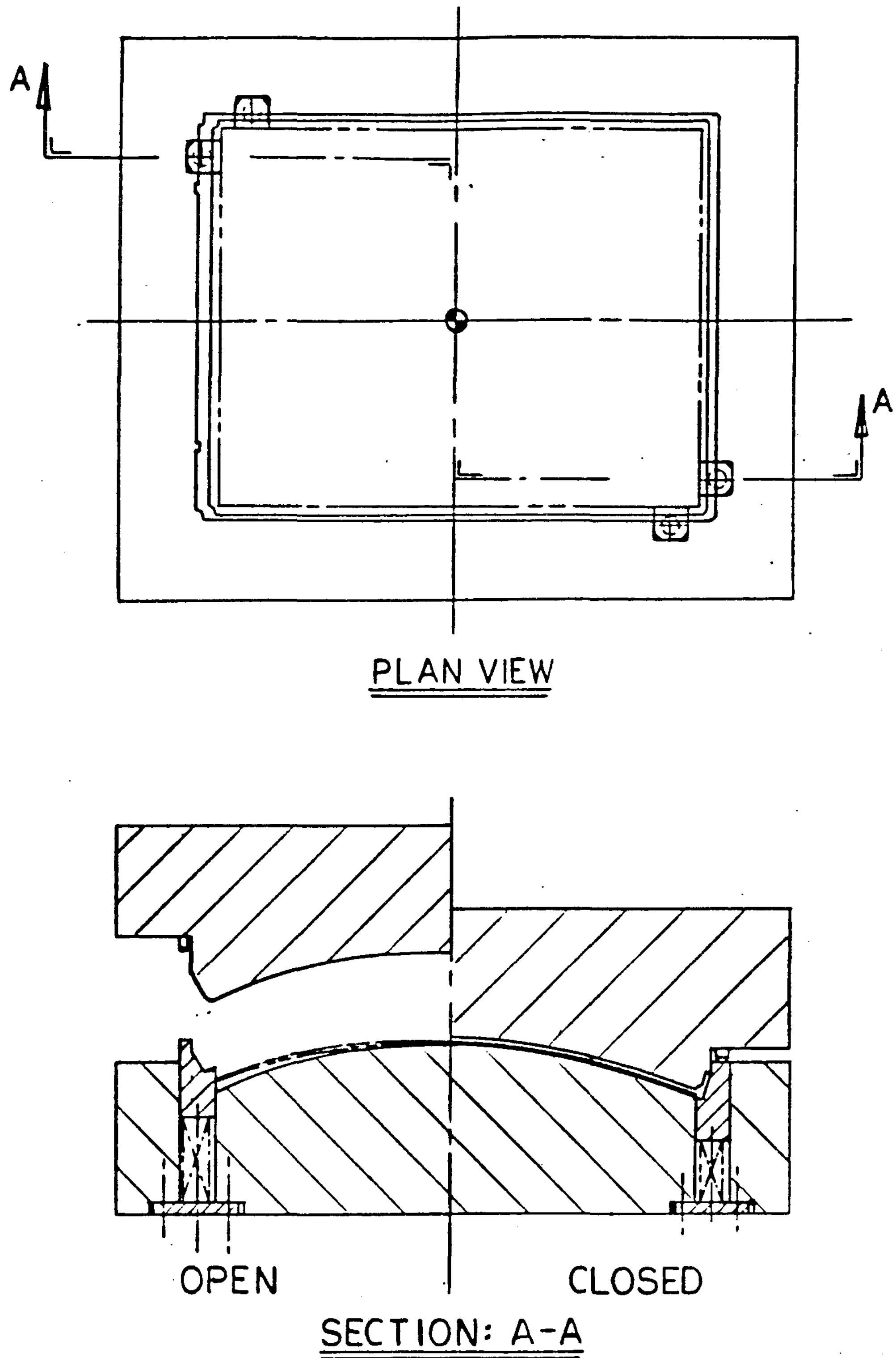


Figure 5 Glass Positioning Using Gaging Blocks - Initial Concept

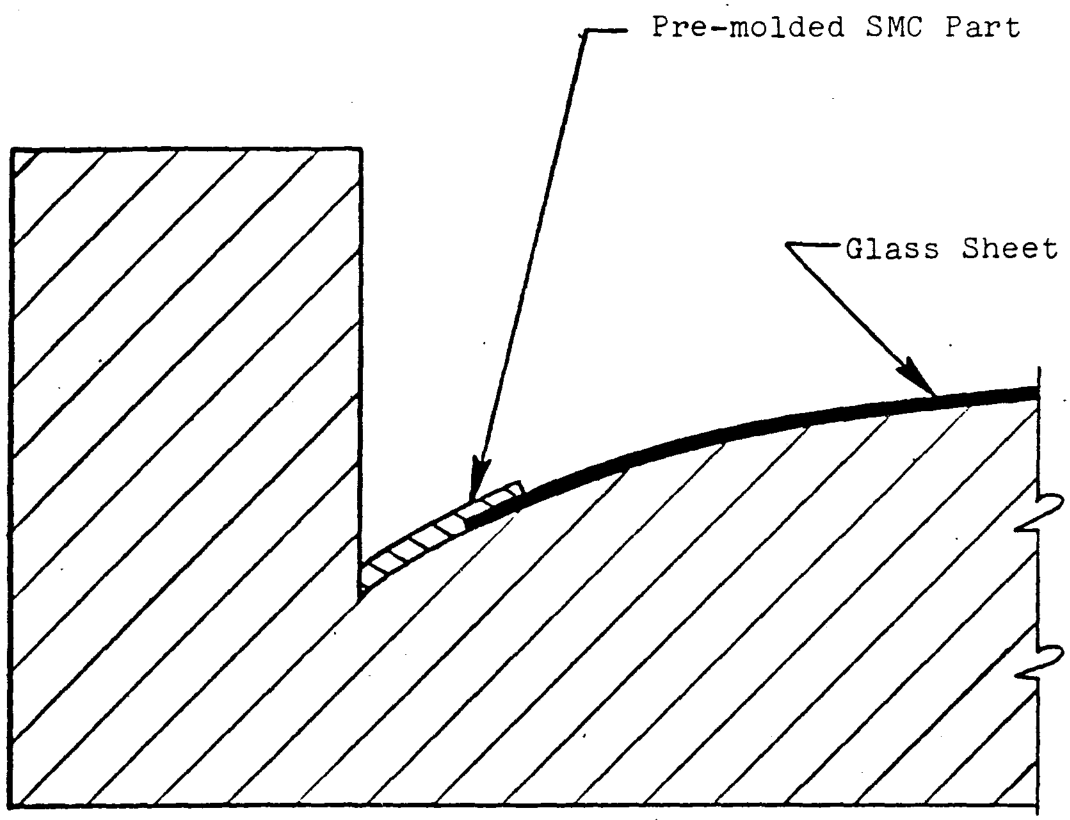


Figure 6 - Glass Positioning Concept Using Pre-molded Parts

assembly. Possible locations were both ends of the one meter width where the cutouts exist for the receiver tube or two positions within the one meter width that would not interfere with the panel assembly. The choice was made to alter the vertex coaming at two internal positions and at the same time provide locating points for the panel assembly. The final design is shown in Figure 7.

Because of a higher thermal expansion coefficient (TEC) of sheet molding compound when compared to glass, the trough panel's radius of curvature - and hence its focal length - would be expected to increase as it cools from the molding temperature to room temperature. Equations predict that the opened shape of the panel remains parabolic. The challenge is to obtain the correct focal length on the finished parts.

One solution would be to account for the change in curvature in the design of the mold. This would entail fabricating the mold to a smaller focal length than is specified for the final part. When the panel is demolded and cooled to room temperature the increase in radius will bring the part to the required curvature. Some assumptions are necessary in this approach: 1) the material properties are known (moduli, poisson's ratios, thermal expansion coefficients); 2) small changes in the cross-section (bosses, longitudinal ribs) are negligible; 3) mechanical isotropy in the plane of the SMC and glass exists; and 4) equations that describe the curvature are accurate. In general, the material properties are known and can be defined by a mean and a standard deviation. Some drawbacks exist to the smaller focal length tooling. These are: 1) when only SMC is molded (no glass mirror) the part will not be

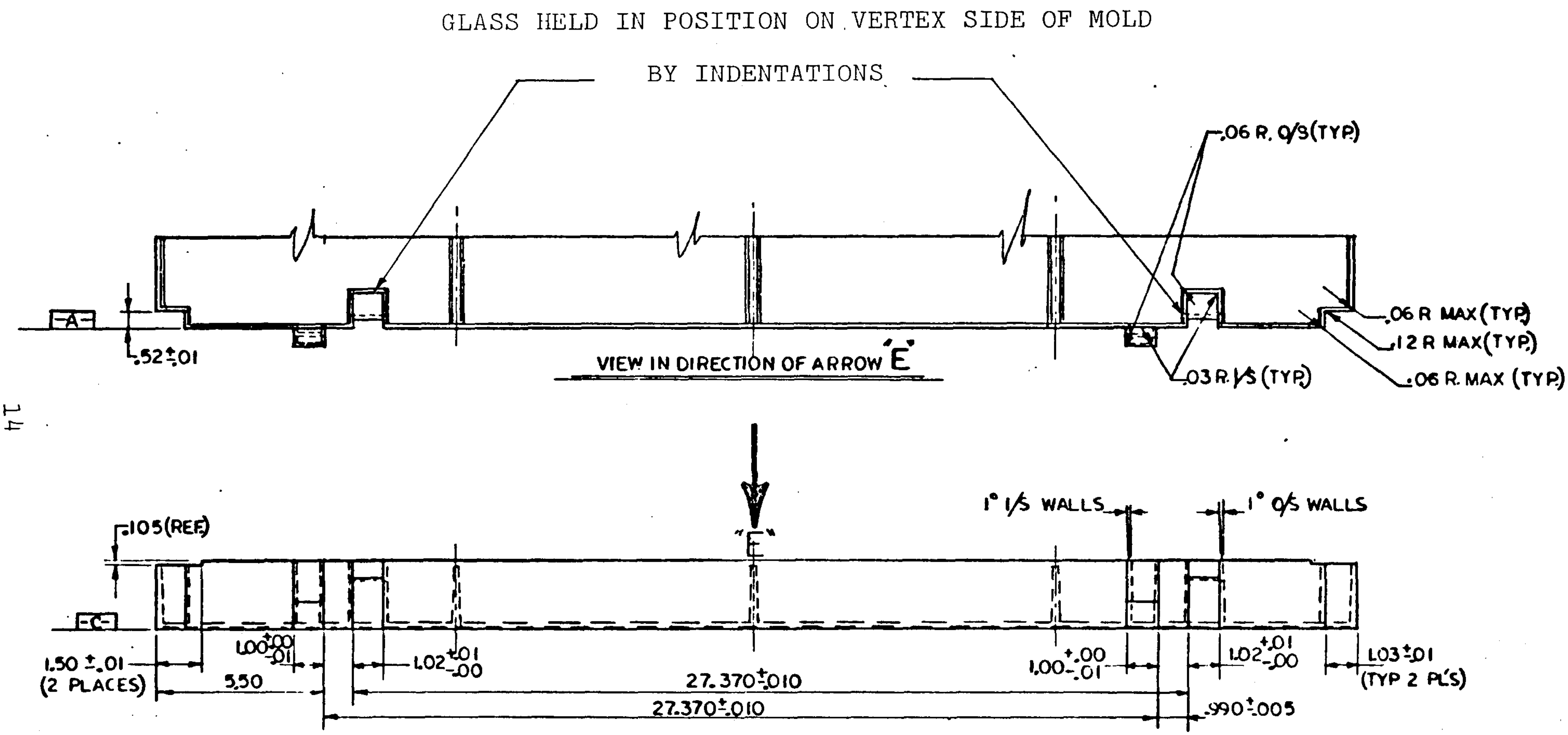


Figure 7 - Glass Positioning - Finalized Design

to the desired shape and 2) when glass of a different thickness than was used in the calculations is molded with the SMC the proper shape again will not be obtained. Despite these drawbacks, the approach of making the trough panel mold to a smaller focal length was chosen as the solution to the thermal expansion coefficient difference between SMC and glass.

The focal length of the trough panel tooling was calculated by Sandia based on the results of previously molded and thermally cycled panels to equal 18.80 inches. Due to the shrinkage of the zinc alloy tooling on cooling from a liquid to a room temperature solid and the expansion in the tooling on heating from room temperature to molding temperature, it was decided to fabricate the template for the mold maker to a focal length of 18.95 inches.

One other consideration in the part design was the ability to mold the boss, Figure 8, to be used as the attachment point from the panel to the torque tube. Based on the experience in molding similar size bosses on automotive grill opening panels, the molding of this attachment boss was not expected to present serious problems.

A full size zinc alloy compression mold was fabricated for producing the trough panels. The mold maker, W.K. Industries, Inc. of Sterling Heights, Michigan, was provided a detail drawing of the part and an 18.95" focal length vertex to rim aluminum template. The reflective side of the mold was constructed of wood and plaster used to form a sand cavity into which the zinc alloy material was cast. The matching tool half corresponding to the rib surface was obtained by applying a wax and wood build-up to account for part

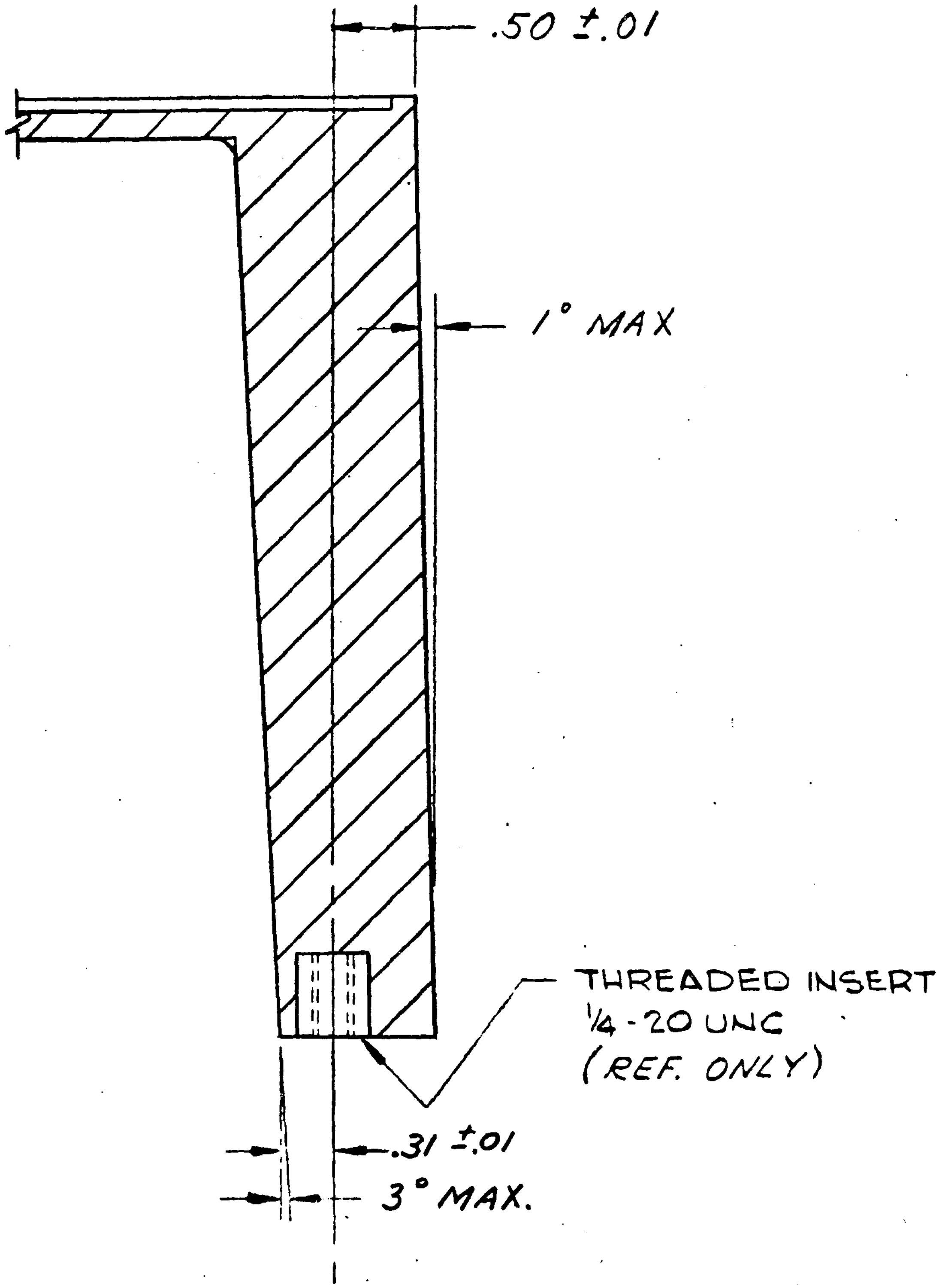


Figure 8. Boss Detail

thickness and rib and boss configuration. Another plaster cast was taken from the built-up structure for use in casting the other half of the zinc alloy tool. Figure 9 gives general information and dimensions on the tool. There are four ejector cylinders that are controlled by a four port flow divider to assure even pressure to all cylinders during ejection. There are a total of thirty five ejector pins of which thirty three are 1/4" diameter and two, located over the bosses, are 1/2" diameter. There are seven ejector pins per rib as shown in Figure 10. Each half of the mold has eight heating lines which follow the parabolic contour to assure even heat distribution. The heating lines are connected as shown in Figure 11.

The trough panel mold is shown in Figures 12 and 13.

2.2 MATERIAL REQUIREMENTS

The material requirements specified for this program were a low shrink, low profile chopped glass fiber sheet molding compound with a vinyl ester or a UV stabilized polyester resin system. Table 2 outlines the material properties as specified by Sandia.

A review of material properties was performed to determine the correct SMC formulation. As can be seen from Figure 14 and Figure 15 (Reference 1) strength in an SMC material is an increasing function of glass content. For the lower end of the 95% confidence limit a tensile strength of 15000 psi corresponds to a glass content of 42% and a flexural strength of 25000 psi

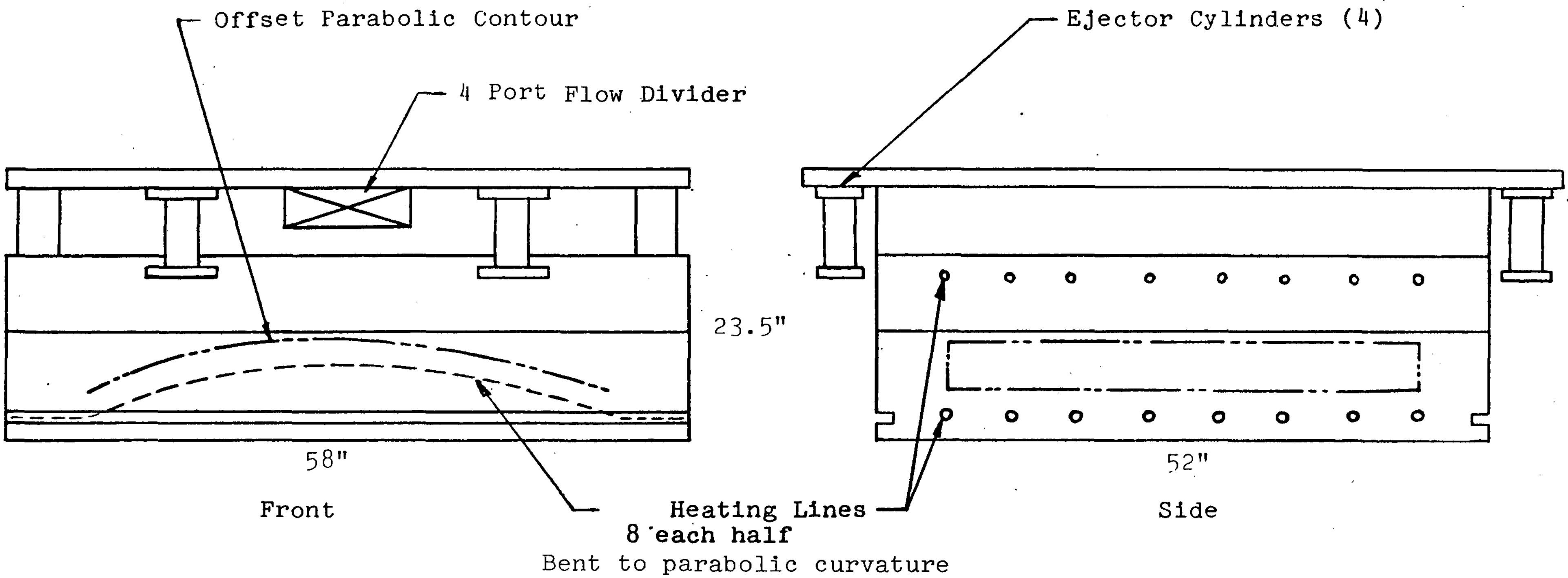


Figure 9. Assembled SMC Trough Panel Mold

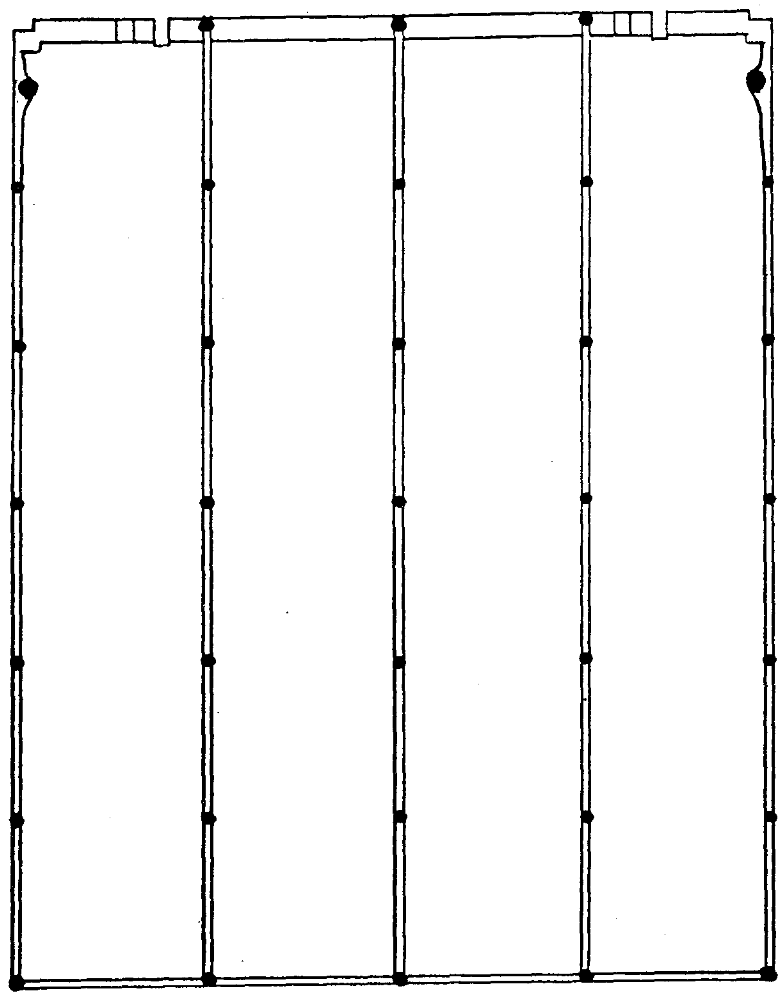


Figure 10. Ejector Pins Location

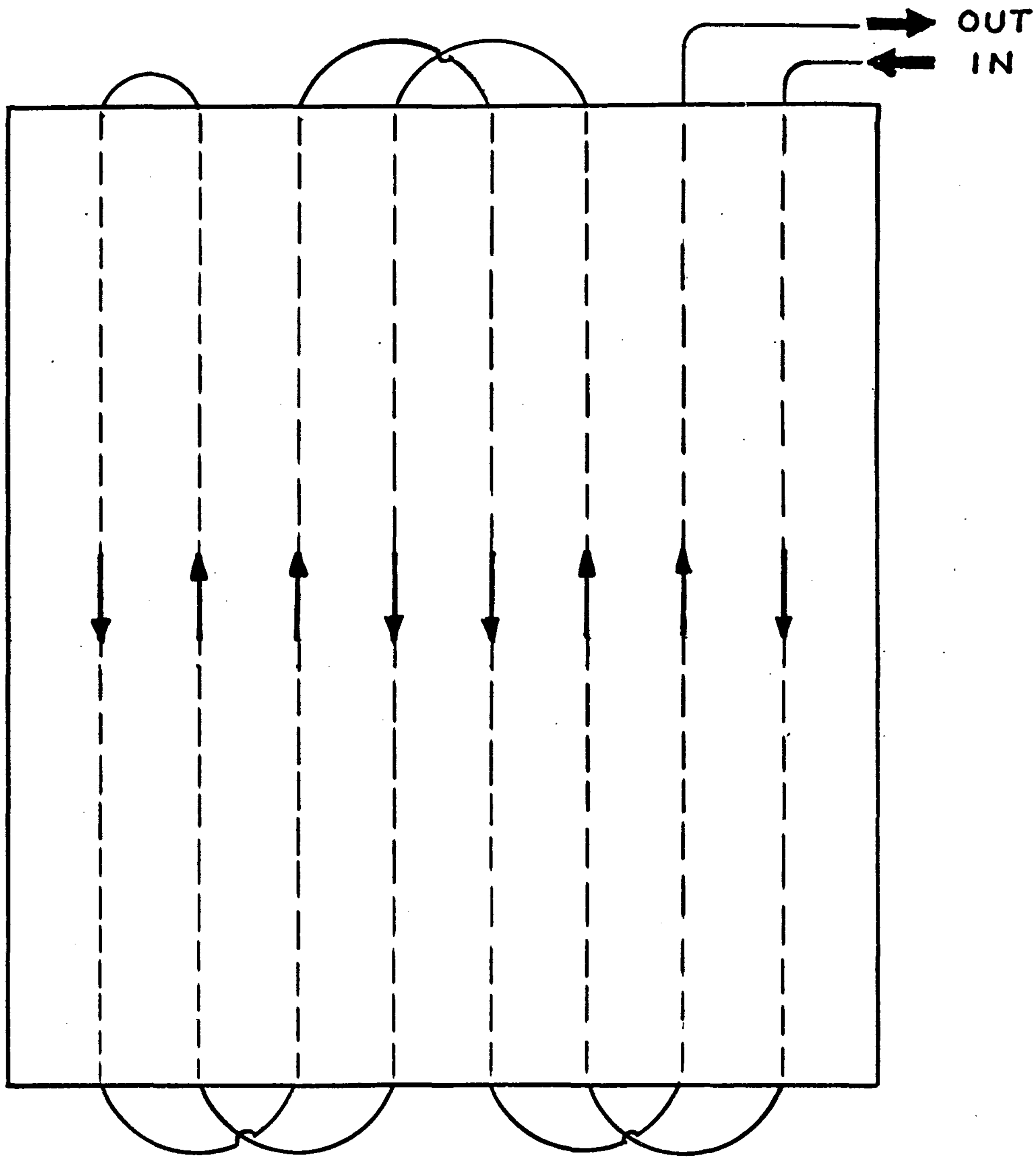


Figure 11. Heating Line Connections

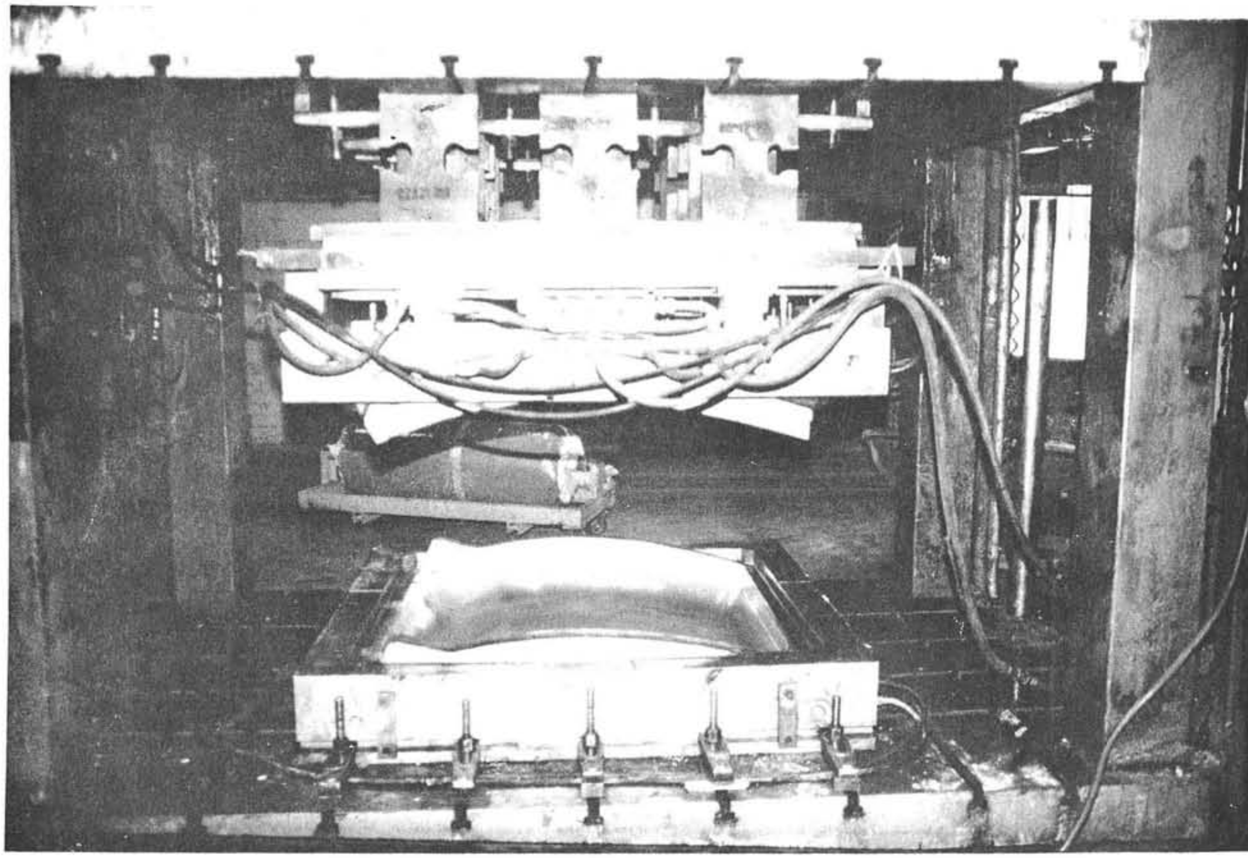


FIGURE 12 - Trough Panel Mold

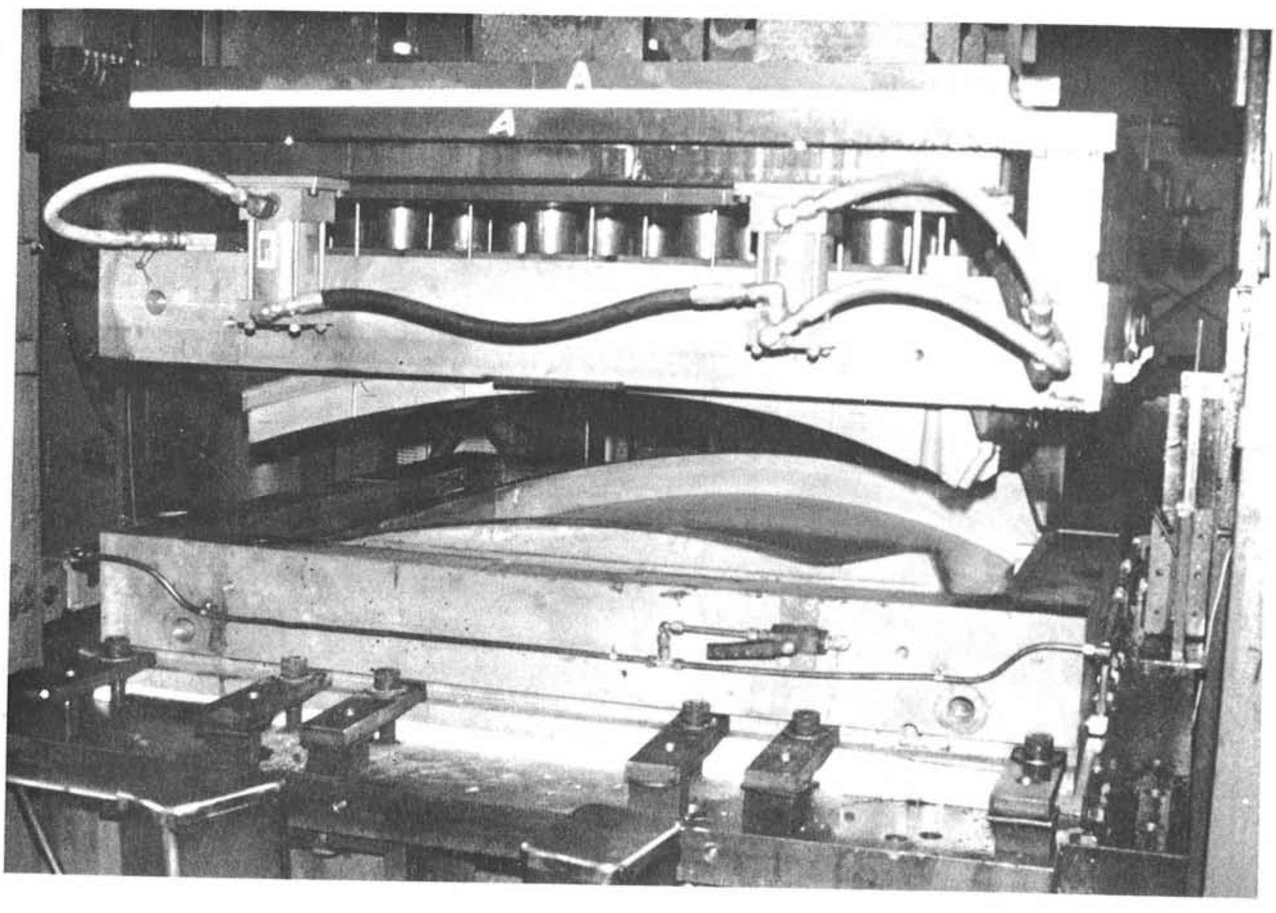


FIGURE 13 - Trough Panel Mold, Another View

TABLE 2 - Material Requirements

Low Shrink, Low Profile

Good Molding Characteristics

UV Stabilized Polyester Resin System

Young's Modulus - 1.5×10^{6} PSI Minimum (1.8×10^{6} PSI Desired)

Tensile Strength - 15,000 PSI

Flexural Modulus - 1.5×10^{6} PSI Minimum (Higher Desired)

Flexural Strength - 25,000 PSI

Thermal Expansion Coefficient (TEC) 6 to 10×10^{-6} in/in/^{O}F

Mechanical Isotropy in the Plane of the Material

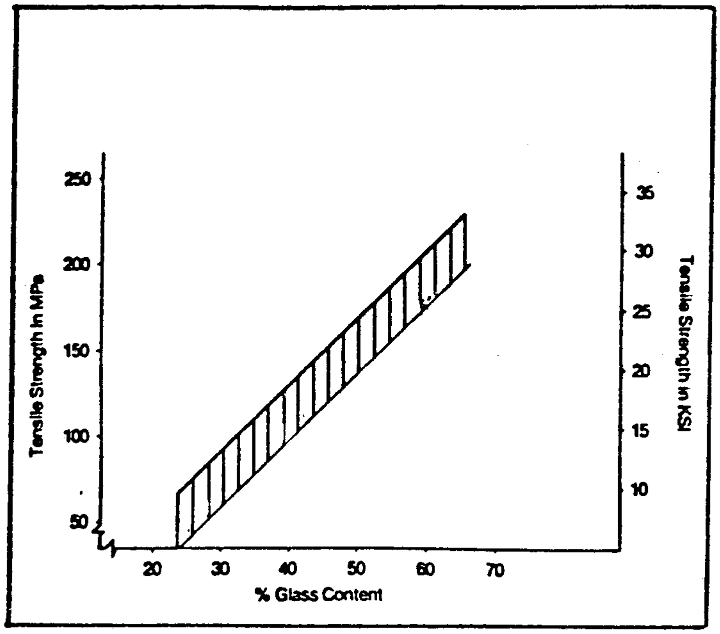


Figure 14. Tensile Strength vs. Glass Content (Reference 1)

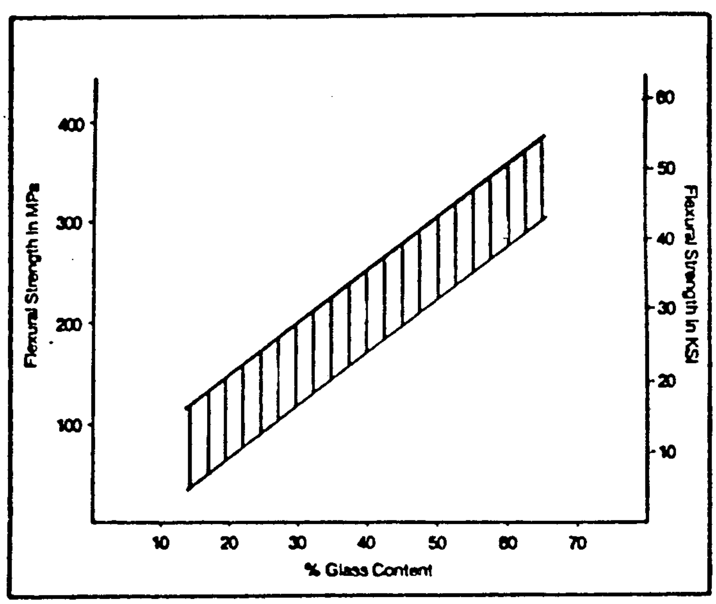


Figure 15. Flexural Strength vs. Glass Content (Reference 1)

requires a glass content of 41%. Average strength and average moduli were also calculated from tests performed by the Budd Company Technical Center as shown in Figure 16 and Figure 17. The tensile strength requirement corresponds to a 42% glass content and the flexural strength requirement corresponds to a 33% glass content as can be seen in Figure 16. Figure 17 indicates that the tensile and flexural moduli requirements of 1.5 million psi are exceeded for glass contents over 25%. The material property review indicated that a 40% content SMC, which is a standard Budd Co. formulation, would exceed the flexural strength, flexural modulus, and tensile modulus requirements and provide 93% of the tensile strength requirement. A 40% glass content SMC was chosen for this program.

Conversations with vinyl ester suppliers indicated that their resins have good chemical resistance but lack good UV properties. For this reason and because UV stabilizers are presently being used in the polyester resin market, a decision was made to use a UV stabilized polyester as the resin system.

2.3 THERMAL EXPANSION CONSIDERATIONS

The selected sheet molding compound is required to have a thermal expansion coefficient no greater than 10×10^{-6} in/in/°F, lower if possible, and equal to that of glass (4.9×10^{-6} in/in/°F) in the ideal case. A review of thermal properties both theoretically and experimentally indicate a range of from 9 to 10×10^{-6} in/in/°F for the TEC. Figure 18 (Reference 2) shows that the TEC decreases with increasing glass content and for a fiber volume ratio of 0.3,

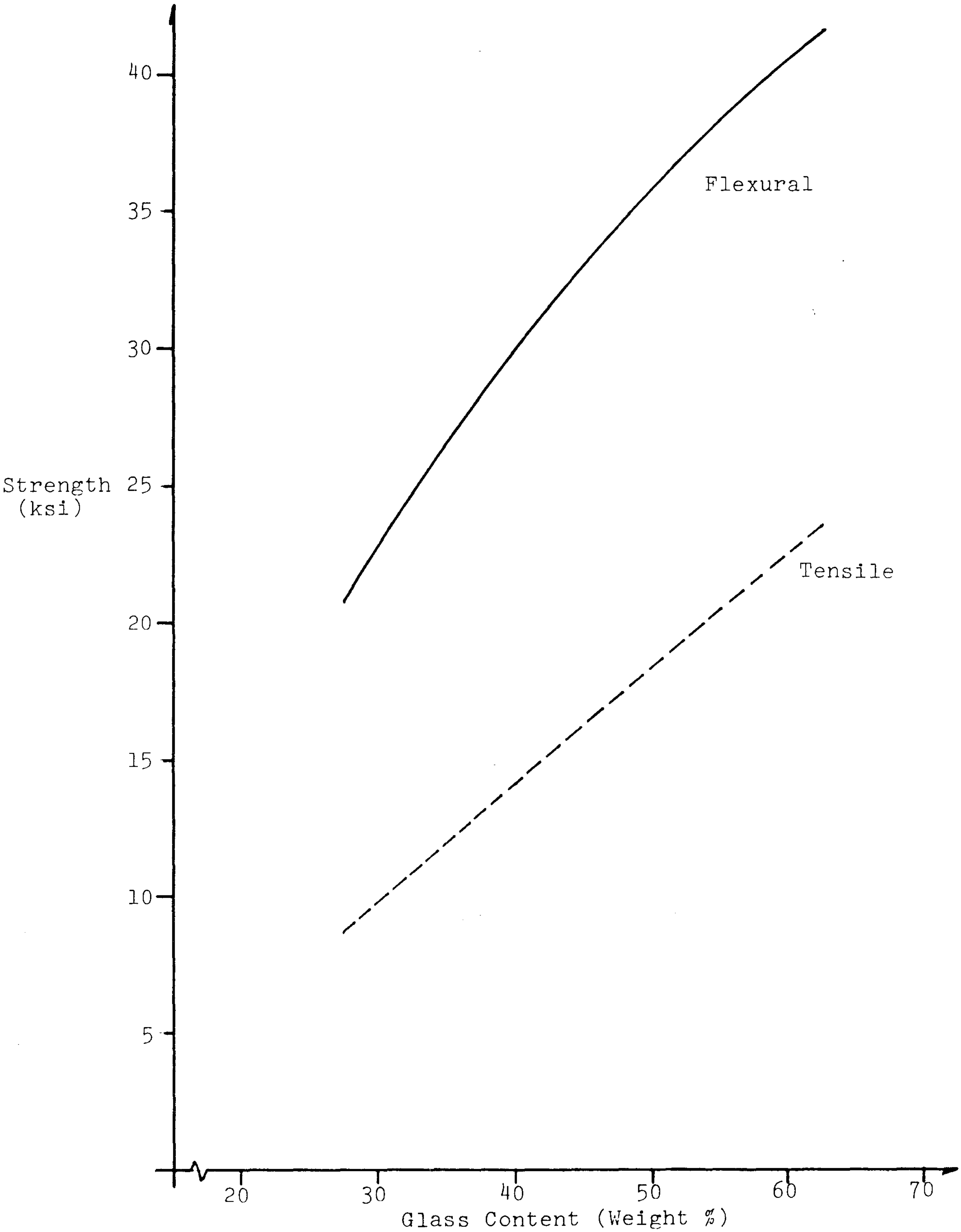


Figure 16. Strength vs. Glass Content
Budd Co. Data

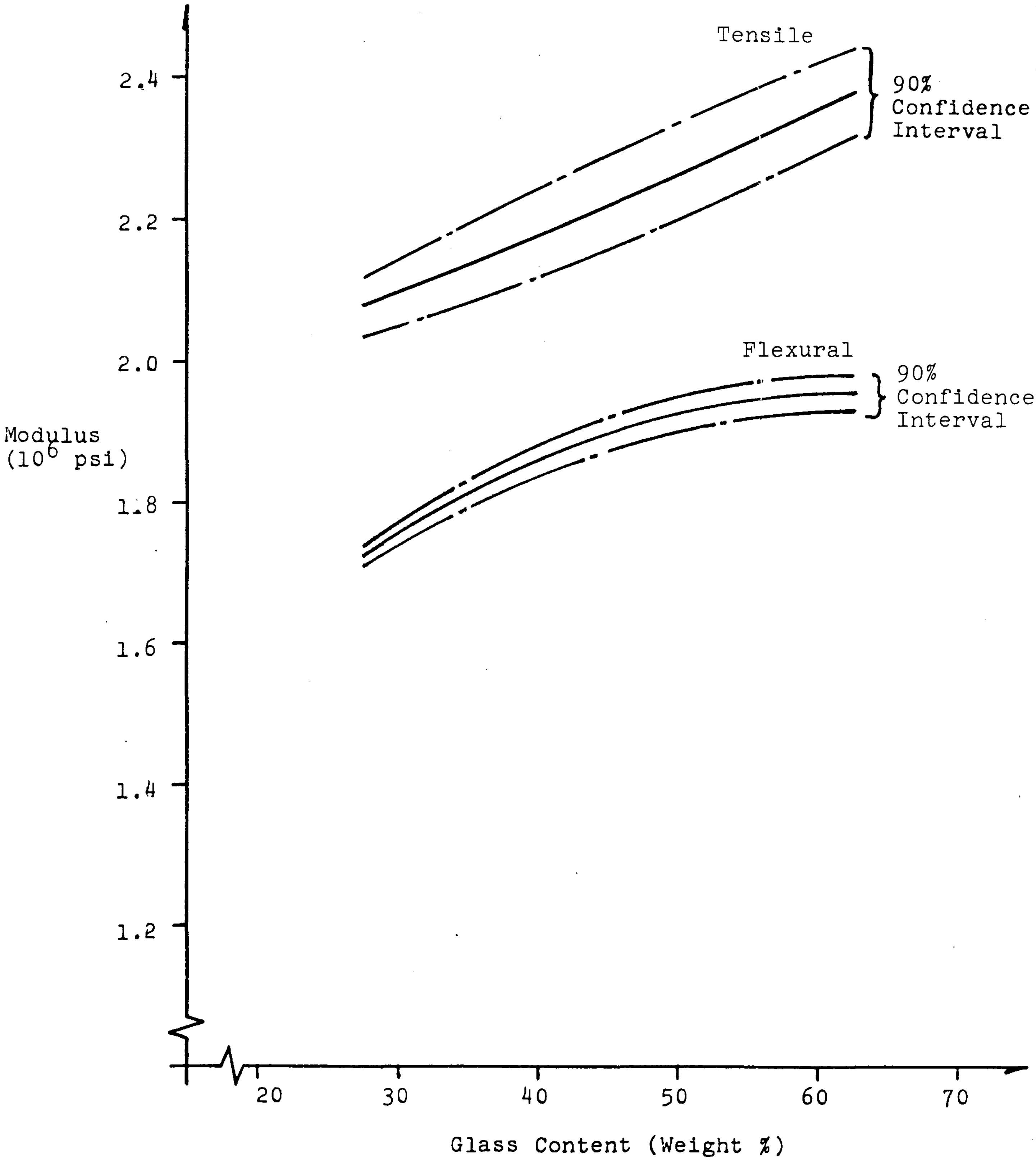


Figure 17. Modulus Vs. Glass Content
Budd Co. Data

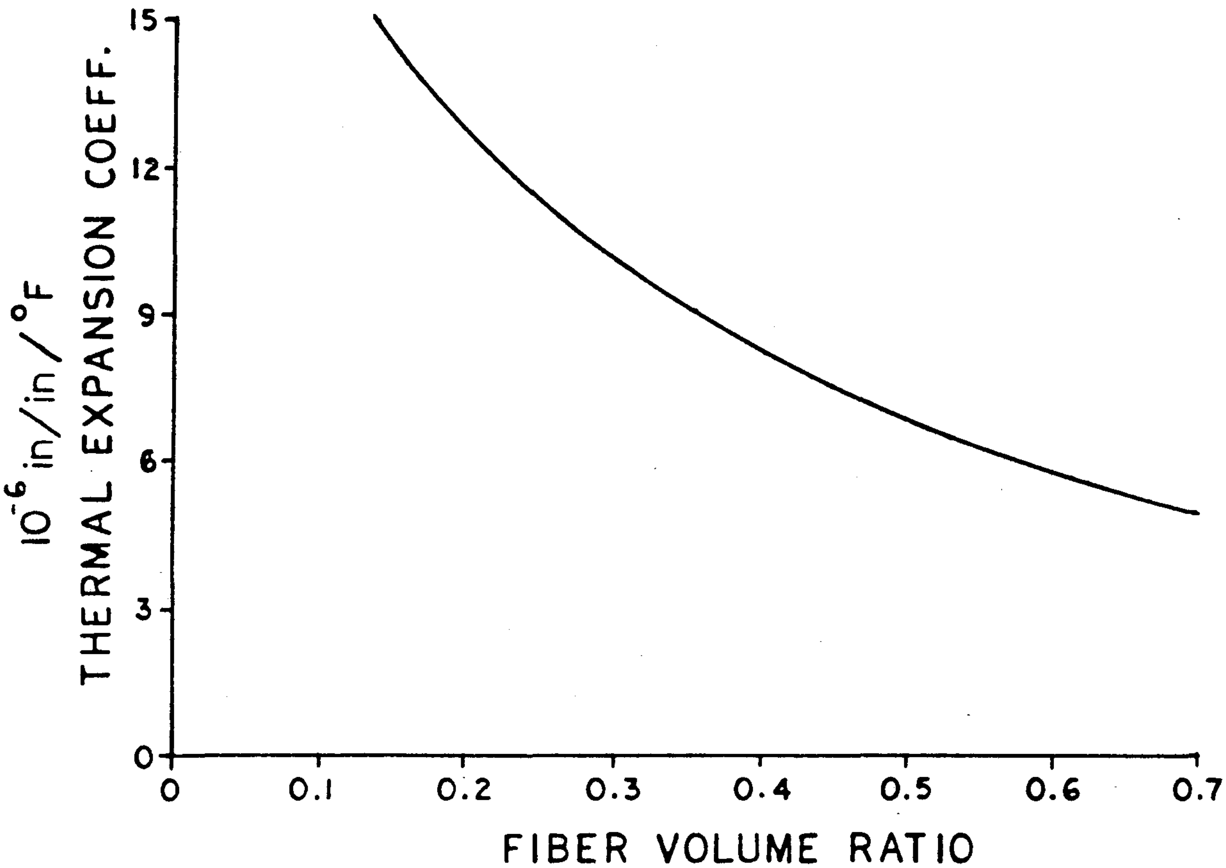


Figure 18. TEC Vs. Fiber Volume Ratio
Theoretical (Ref. 2)

which is approximately a 40% weight content, the TEC is equal to 10×10^{-6} in/in/°F. Figure 19 (Reference 3) shows that the thermal expansion coefficient decreases with temperature above room temperature and is equal to 9.2×10^{-6} in/in/°F for a 50% glass content at room temperature. To achieve a lower value would entail some additional research, not provided in this contract, in the area of additives such as carbon fibers, Wollastonite or processed mineral fiber. Table 3 (Reference 4) gives the thermal expansion coefficients of various thermoplastic composites with no reinforcements, 30% glass reinforcement and 30% carbon reinforcement where the TEC is consistently lower with the carbon reinforcement compared with the glass reinforcement. Table 4 (Reference 5) gives similar results when comparing Wollastonite with glass in a Union Carbide RIM 125 material. It does appear possible to reduce the thermal expansion coefficient by using different reinforcements and fillers although the effects of these additives on other properties are unknown. It is expected, however, that the cost of the sheet molding compound with the additives will increase.

In summary, the chosen SMC formulation is a low shrink, low profile SMC using 40% by weight one inch chopped glass fibers in a UV stabilized polyester resin matrix. Before delivery of this formulation it was decided to calculate the thermal expansion coefficient and insert pull out strength of similar SMC materials, to be followed by determination of the chosen material properties as outlined later in the report.

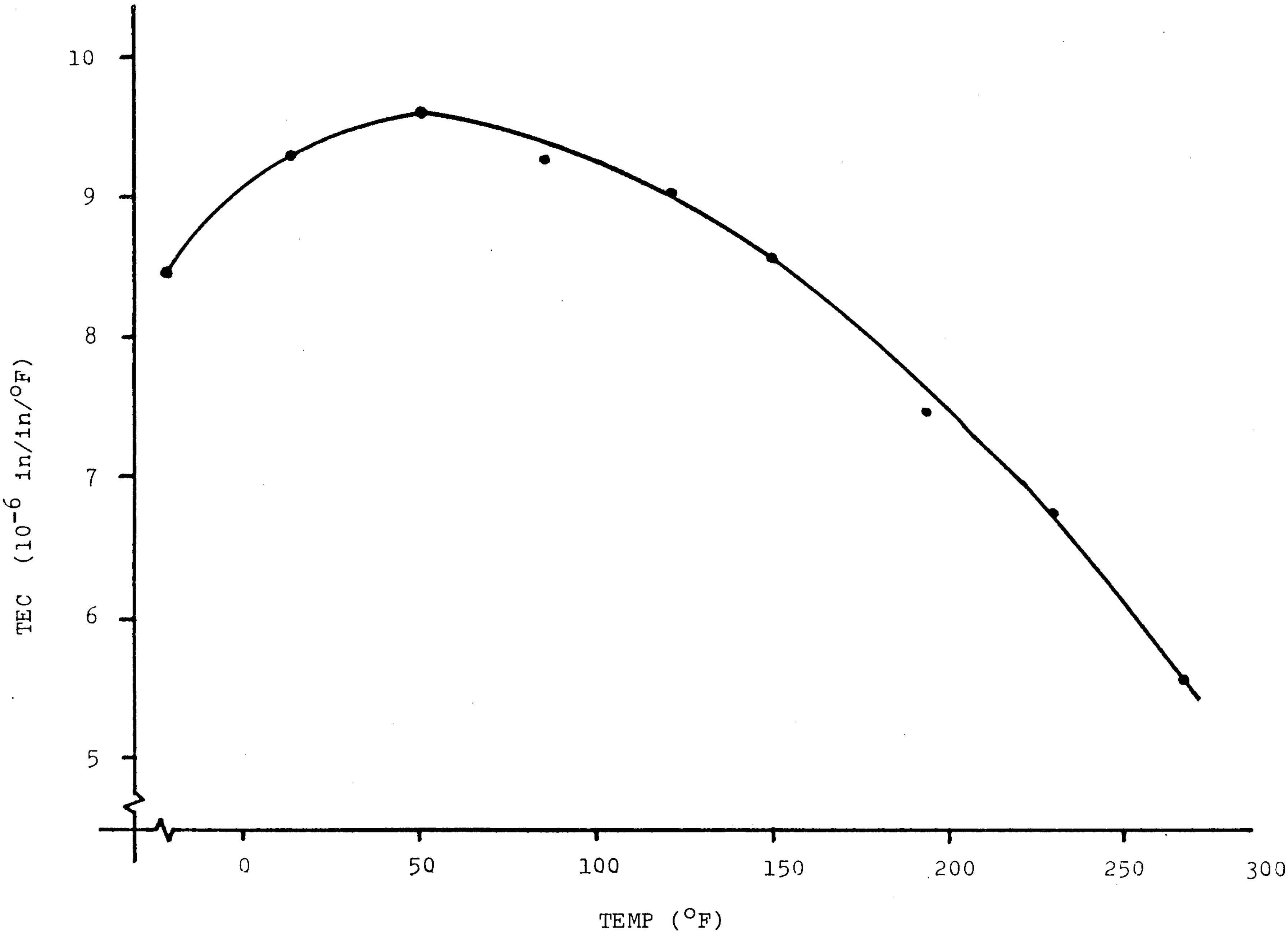


Figure 19. TEC vs. Temperature for SMC-R50 (Reference 3)

TABLE 3 - Thermal Expansion Coefficients of Various Thermoplastic Composites (Reference 4)

MATERIAL	UNREINFORCED	REINFORCEMENT 30% GLASS	30% CARBON
Nylon 6/6	45	13	10.5
Polysulfone	31	14	7
Polyester	53	12	5
Polyphenylene Sulfide	30	13	6
Ethylene TFE	42	17	8

(VALUES SHOWN ARE 10^{-6} IN/IN/^{o}F)

TABLE 4 - Thermal Expansion Coefficients (TEC) Union Carbide RIM125 Composites (Reference 4)

FILLER	Wt %	TEC (10^{-6} IN/IN/^{o}F)
None	-	55.0
1/16" Milled Glass Fiber	16	34.1
Wollastonite	17	24.2
	32	22.6
Processed Mineral Fiber	17	34.0
	29	26.0

Thermal expansion coefficient tests were done on four specimens cut from each of three glass content SMC moldings to get an idea of actual TEC values. The method entailed placing a three inch long by one half inch wide specimen in a quartz tube dilatometer per ASTM Standard D696-70. Results are given in Table 5.

2.4 INSERT/MATERIAL INVESTIGATION

The final panel design utilizes an insert in the boss as the attachment point for the panel to torque tube connection. Requirements of the boss and insert are internal 1/4-20 threads and a tensile load of 200 pounds. There are a variety of metal inserts for plastics use, such as molded-in, interference fit, expansion, self-threading and threaded-in inserts. Interference fit and expansion inserts require that the insert be installed in a molded-in or drilled hole by a pressing or hammering operation which does not agree with the brittle nature of SMC. The threaded-in insert requires that a hole be drilled and tapped before installing the insert (Reference 6). Self threading inserts cutting action locks the insert in place to provide strong thread surfaces that resist torsional and tensile loads. The size of the hole is critical as oversize holes result in poor strength conditions while undersize holes require excessive driving torque and may induce premature failure of the boss.

A stress analysis of the part shows that the tensile and shear stresses are within the limits of the material. Figure 20 shows

TABLE 5 - Preliminary Test Results of Thermal Expansion Coefficients.

MATERIAL	TEMPERATURE RANGE 0-75	75-135	135-200	0-200 Overall
SMC-27%	10.33	11.47	10.29	10.67
SMC-40%	9.43	9.35	6.35	8.52
SMC-62%	9.65	6.26	5.31	7.70

Values in the table are 10^{-6} in/in/$^{\circ}$F the boss-insert area. Assume that the boss diameter is a constant 5/8" and the insert diameter is 7/16". The tensile stress is

$$\sigma_T = \frac{P}{\frac{\pi}{4}\left[\left(\frac{5}{8}\right)^2 - \left(\frac{7}{16}\right)^2\right]} = 6.39P$$

The shear stress is

$$\tau = \frac{P}{(.9)(\pi)\left(\frac{7}{16}\right)(.425)} = 1.90P$$

Where 0.9 is a factor used to compensate for the area of the threads.

For a load of 200 lbs., σ_T = 1280 psi and τ = 380 psi, which affords safety factors of 11 on the tensile stress and 5 on the shear stress. Although this analysis indicates large enough safety factors, tests were performed on insert-boss assemblies.

Five bosses were cut from a grill opening panel (the front outer panel of an automobile containing headlamps and an opening for the grill) molded with a 25-30% low shrink, low profile sheet molding compound. These tests were done to get a better feel for possible problems. The bosses were a nominal 5/8 inch diameter at the narrow end and 3/4 inch diameter at the larger end, with lengths ranging from 1.5 inches to 2 inches. See Figure 21.

Two different makes of inserts were installed in the bosses. The first type, a Trisert Insert is proclaimed to be a self-tapping insert. However, when attempting to thread the insert into the recommended size drilled hole, the boss cracked due to the brittle-

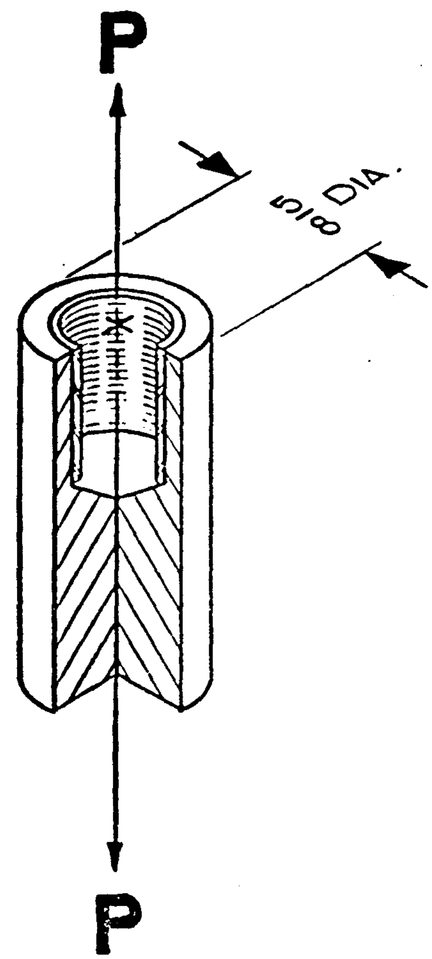


Figure 20. Boss-Insert Area

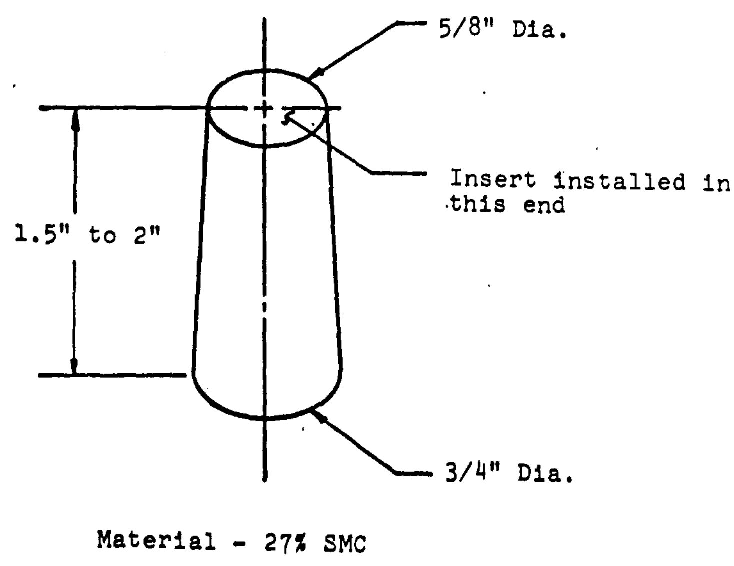


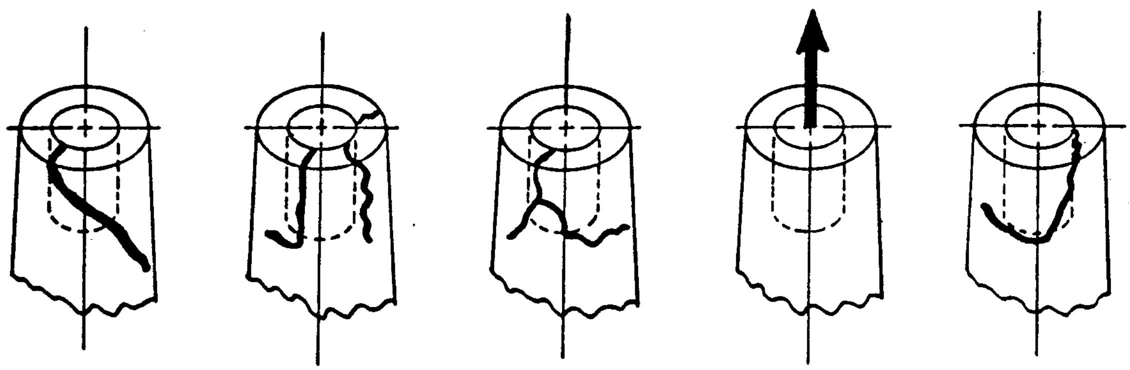
Figure 21. Boss Used for Preliminary Insert Pull Out Tests

ness of the SMC. Two larger holes were drilled until the boss did not crack when threading the insert.

The second type of insert is the E-Z Lok insert which is fabricated with a standard external thread (see Appendix A for product literature). The boss must be drilled and tapped first, and when threading the insert microencapsulated epoxy molecules are broken and begin to cure, apparently locking the insert into the boss.

To test the pull-out strength a hole was drilled through the entire length of the boss, assuring in-line tensile loads and minimizing bending. The large end of the boss was drilled and tapped to accommodate a threaded rod which is attached to the tensile machine. The 0.375 inch diameter Trisert insert was threaded into a 0.360 inch diameter drilled hole, leaving only 0.0075 inch engagement of the thread and the SMC. A threaded rod was used to connect the insert to the testing machine. Before testing began it was thought that the Trisert insert would not perform as well as the threaded in E-Z Lok insert because of the low thread/material engagement.

Results of the pull-out tests are shown in Figure 22. The three E-Z Lok inserts did not pull-out but caused cracking in the bosses. One Trisert Insert also caused cracking while the other Trisert started to pull-out before cracking occurred. If any conclusions can be drawn from these tests it is that as long as the insert stays attached to the boss then what is being measured is the material property, not the insert strength. The test



Test:	1	2	3	4	5
Failure:	Crack	Crack	Crack	Pull-Out	Crack
Max Force:	850	862	770	675	895
Insert:	E-Z Lok	E-Z Lok	E-Z Lok	Trisert	Trisert

Figure 22. Preliminary Insert Pull-Out Test Results

results indicate that the most important function of an insert is its ability to be consistently made an integral part of the boss. At this time the Trisert-Insert does not seem to offer this consistency, whereas the E-Z Lok insert does.

The decision was made to use E-Z Lok inserts and perform pull-out tests on bosses cut from molded panels at a later date. This data is reviewed later in the report.

2.5 FIXTURE DESIGN AND FABRICATION

The fixtures required for this project are described below.

An oven was necessary for preheating of the glass to avoid thermal shock on the glass as it is placed in the hot mold, to assist in the flow of the SMC across the glass, and to provide an increased chance of the SMC wetting and adhering to the coated surface of the glass. The oven was fabricated to accommodate one sheet of glass in the horizontal position. Standard electrical strip heaters were used in conjunction with a temperature controller to keep the preheat temperature at $250^{\circ}F$. The oven consisted of one inch thick insulating material lined internally with aluminum for heat reflection and externally with plywood for rigidity.

Two cooling fixtures, Figure 23, were fabricated to hold the molded trough panel when cooling from the molding temperature to room temperature. The cooling fixtures were made by first constructing a female wooden model to the correct parabolic contour and then taking two male castings of fiberglass mat and polyester resin with a wood support from the female model.

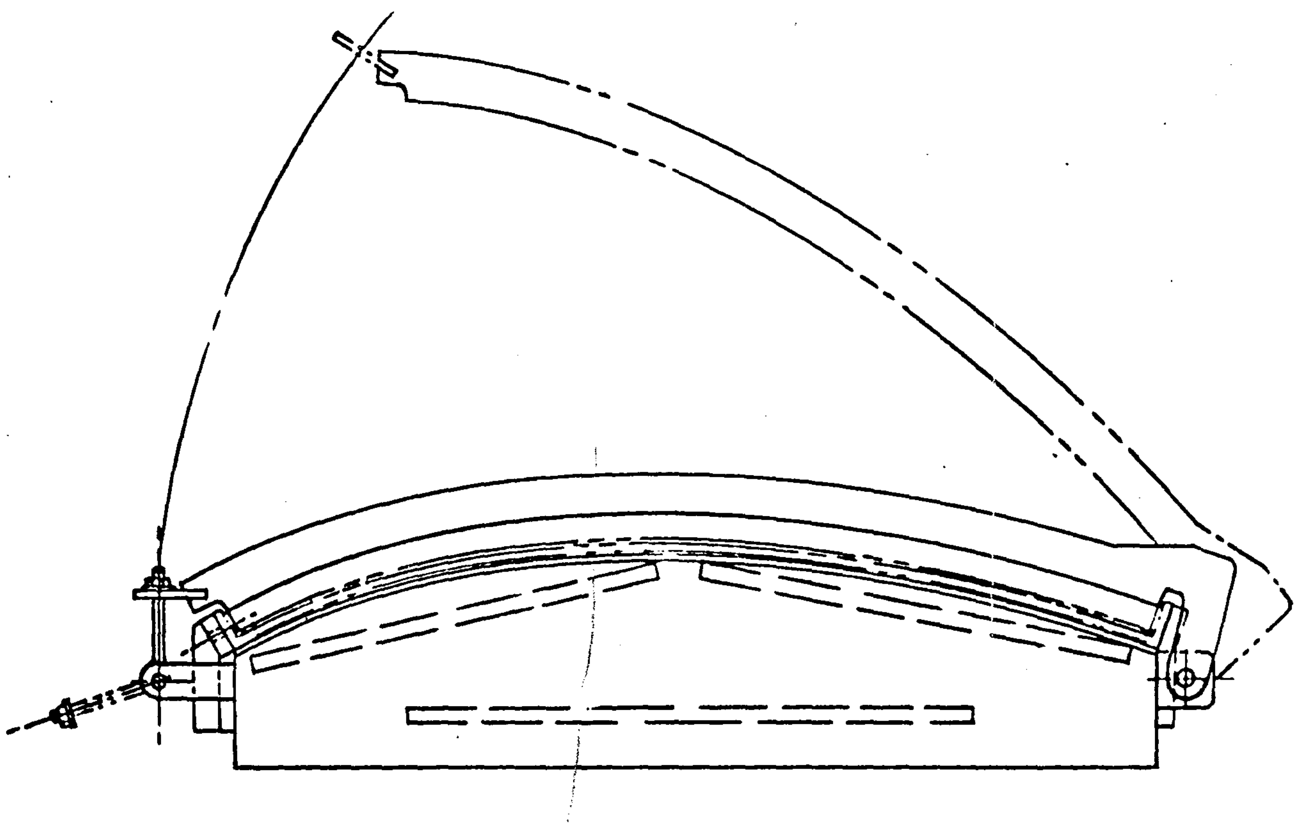


Figure 23. Cooling Fixture-Initial Concept

The storage and shipping rack concept is shown in Figure 24. Five racks, one to hold four panels and four to hold eight panels each, were constructed for safe shipment of the reflector panels.

The inspection fixture is shown in Figure 25. This fixture held the assembled 2 meter by 1 meter panel in a horizontal position for the inspection performed by a three axis digitizing machine, which for a given X and Z coordinate value determines the Y position. More information on the inspection is given later in the report.

2.6 PRELIMINARY SMC-GLASS ADHESION TESTS

Flat, sample size moldings were made of sheet molding compound and painted mirrored glass to investigate the adhesive strengths between the multiple layers on the mirror. The mirror coatings on the glass consist of approximately 1000 Angstroms (3.9×10^{-6}in.) of silver, approximately 300 Angstroms (1.2×10^{-6}in.) of copper, plus a protective paint of approximately 0.004 inch thickness. Eight 10" x 12" glass mirrors, provided by Sandia Labs, were furnished to Budd with PPG Mirro-Chron 44410 paint. On four of these mirrors the paint was removed, making sure that no visible damage was done to the copper surface. One of these mirrors was coated with a commercially available lacquer primer paint, one with an enamel primer paint, and two with an epoxy coating which is Key Polymer Corp.'s E-12 epoxy. One each of the mirrors with the Mirro-Chron paint, the lacquer paint, the enamel paint, and the epoxy coating were cut into 1.5" squares for future tensile and shear tests. The remaining four 10" x 12" mirrors

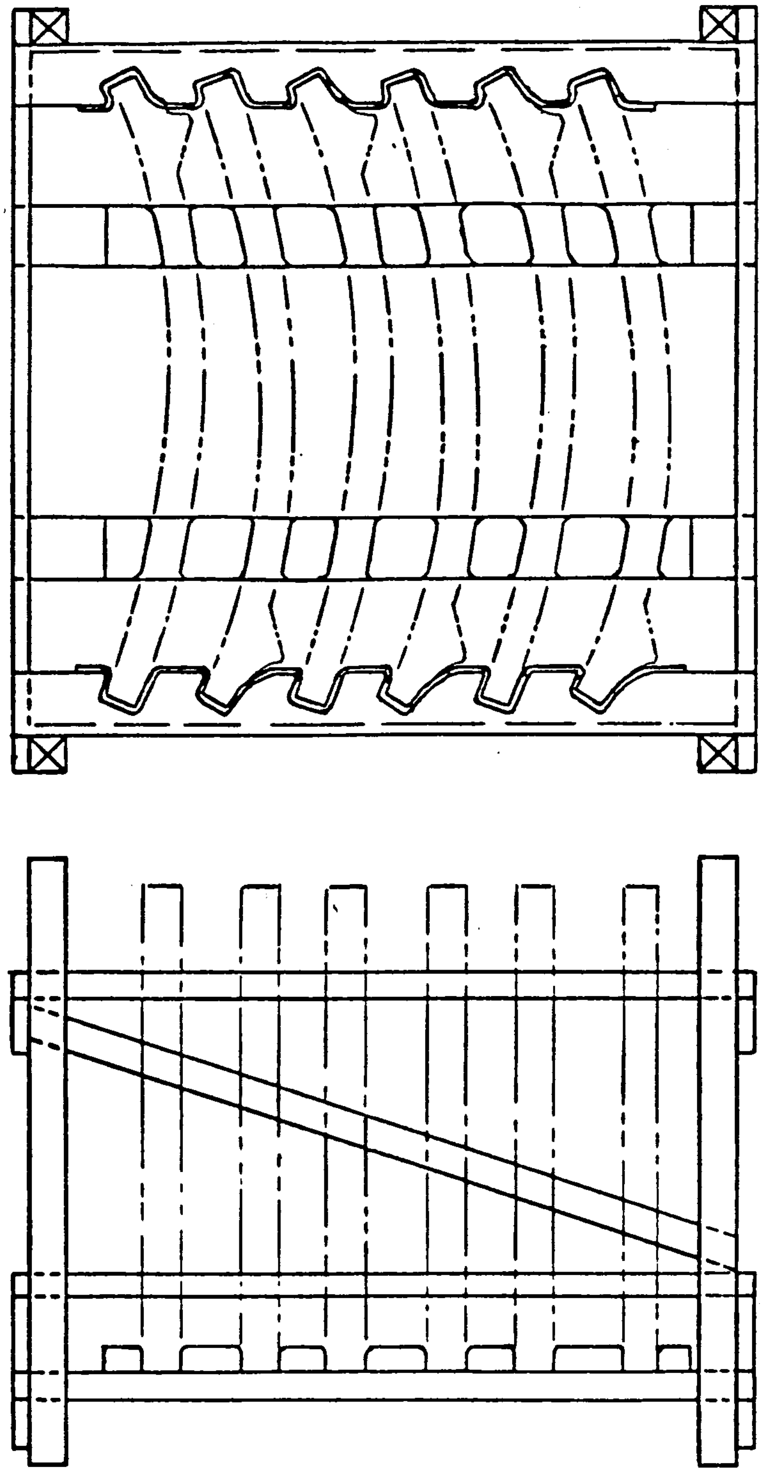


Figure 24. Storage and Shipping Rack Concept

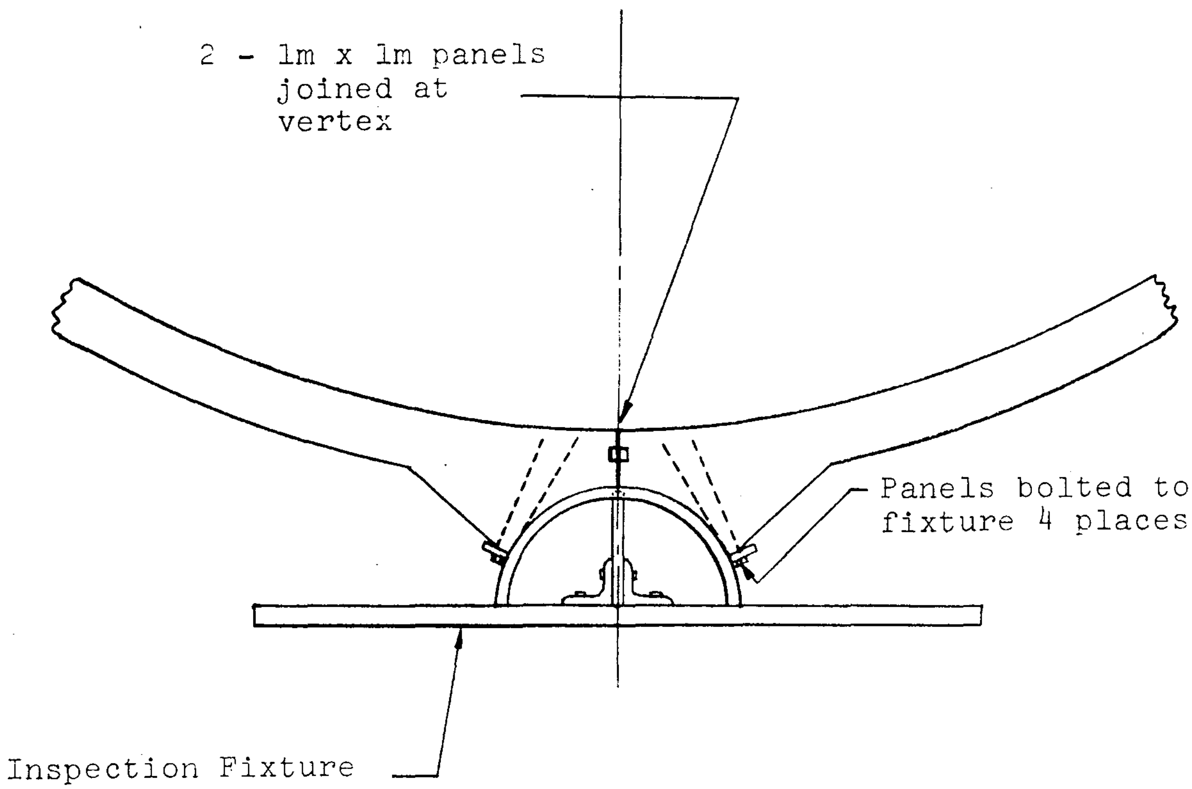


Figure 25. Inspection Fixture

were kept intact. Nine 10" x 23" glass mirrors, provided by PPG Industries through Sandia Labs, were coated, three each, with three different systems labeled A, B, and C. One each of the B and C mirrors were cut into 1.5" squares for further testing.

Tests were also made on the adhesion of SMC to glass with the same E-12 epoxy coating sprayed over the existing Mirro-Chrom 44410 paint. Additional moldings were made at a later time where a PPG supplied paint 44498 was sprayed over mirrors with the existing Mirro-Chron 44410 paint. It was also sprayed over mirrors after the Mirro-Chron paint was removed and only the silver and copper coatings remained. Moldings were made on these two types of glass and also on the Mirro-Chron coated glass, each with and without a coating of a catalyzed polyester resin. Table 6 gives an outline of the coating system and the quantity molded with SMC.

The molding procedure consisted of placing the mirror in a 300°F. flat plaque mold from five to ten minutes to assure proper preheating of the glass. The SMC charge pattern, which varied from 60% to 80% mold area coverage, was placed on the glass and the mold was closed. The cycle time was three minutes at a nominal pressure of 700 psi. The molded parts were ejected and allowed to cool to room temperature before any tests were performed.

There were two testing procedures used to determine the adhesion. The first test, which was basically a subjective test, consisted of bending and twisting the molded glass-SMC panel in an attempt to dislodge the glass from the SMC. This test was

TABLE 6 - SMC - Glass Preliminary Tests-Coating Systems and Quantity

COATING SYSTEM		QUANTITY MOLDED WITH SMC	
		LARGE SIZE (10" x 12")	SMALL SIZE (1.5" x 1.5")
PPG	Plain	2½	10
	with Polyester Resin	2½	-
Enamel Primer (Spray can)	Plain	-	10
Lacquer Primer (Spray can)	Plain	-	10
PPG EP138-83-A	Plain	½	-
	with Polyester Resin	½	-
PPG EP138-83-B	Plain	1½	10
	with Polyester Resin	½	-
PPG EP138-83-C	Plain	1½	10
	with Polyester Resin	½	-
Key Epoxy E-12	Plain	1	10
	with Polyester Resin	-	-
	over 44410	2	-
PPG 44498	Plain	1	-
	with Polyester Resin	1	-
PPG 44498 over 44410	Plain	1	-
	with Polyester Resin	1	-

used on the 10" x 23" and the 10" x 12" mirrors. The second procedure, which was quantitative and was used on the 1.5" square molded mirrors, consisted of cutting the glass-SMC laminate into a 1.5" square unit and testing this unit in a flat-wise tensile test or an interlaminar shear test. These two testing fixtures are shown in Figure 26.

Results of the bending and twisting subjective tests are given in Table 7. Failure could possibly occur at any interface; that is, glass/silver, silver/copper, copper/paint,and paint/SMC. In addition, cohesive failure could occur within any one of these coatings; such failures were most often seen within the paint. Since these tests were not quantitative and failure was forced to occur, the initial concept of these tests was to better understand basic adhesion characteristics of various coating materials as they respond to the molding process. After some full size reflector panels were molded, these tests were further used to correlate what was happening in the full size panels versus what was occurring in the test pieces. Table 7 shows that the unconditioned 44410 paint did not provide as much adhesion as some of the other coating systems used. Two questions arose at this point: (1)What coating system was good enough to provide acceptable reflector panels? and (2) Were the test pieces simulating the actual molding process of the full size panels?

The answer to the first question was the development of the flatwise tensile and the interlaminar shear tests. Results of these tests are shown in Table 8, where all of the samples were tested at room temperature. The epoxy coating obviously provided

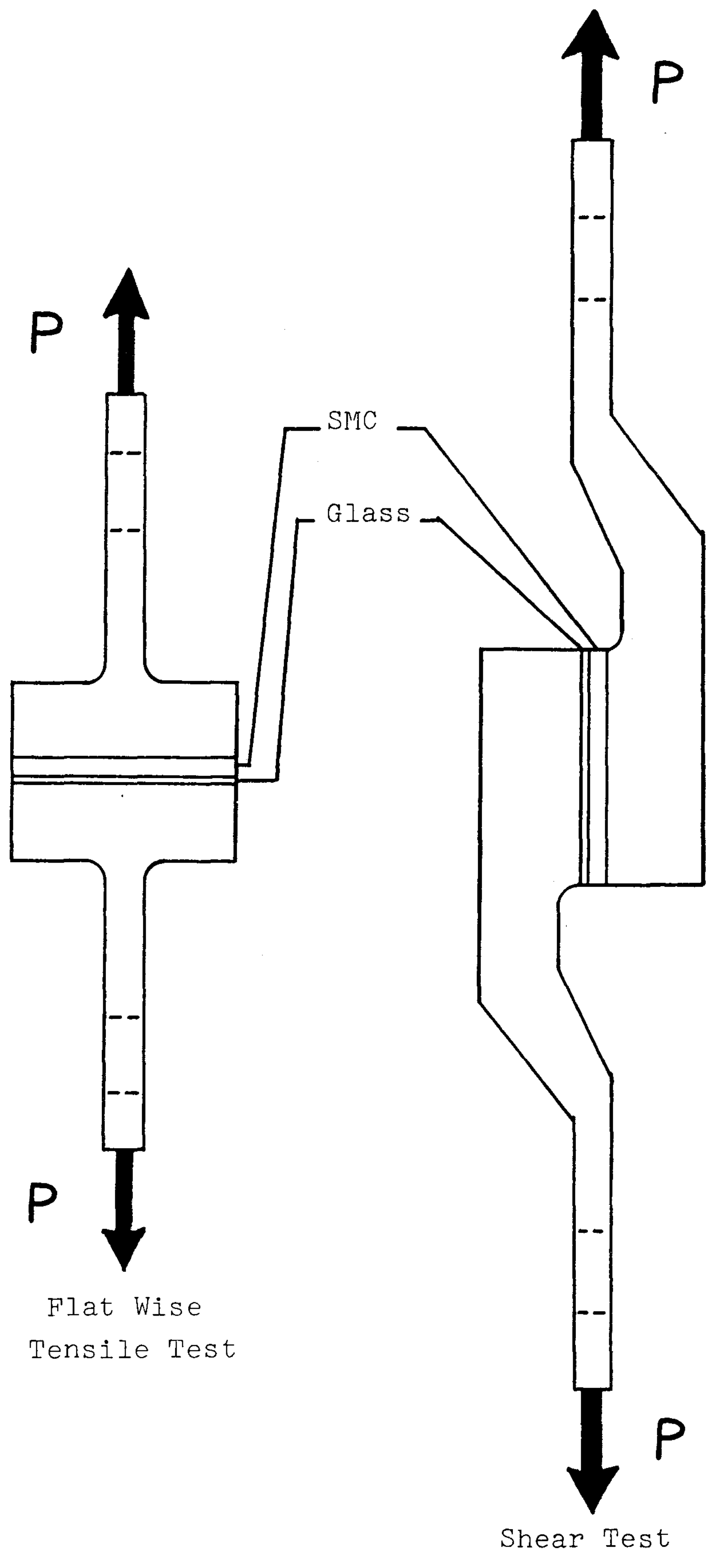


Figure 26. Testing Fixtures for SMC/Glass Laminate

TABLE 7 - SMC - Glass Preliminary Tests-Subjective Test Results

COATING SYSTEM		FAILURE MODE
PPG 44410	Plain	90% between SMC and 44410 10% between 44410 and copper
	with Polyester Resin	30% of glass adhered to SMC 70% between paint and copper
PPG EP138-83-A	Plain	100% between SMC and "A"
	with Polyester Resin	100% between SMC and "A"
PPG EP138-83-B	Plain	50% of glass adhered to SMC 50% between "B" and copper
	with Polyester Resin	50% of glass adhered to SMC 50% between "B" and copper
PPG EP138-83-C	Plain	80% of glass adhered to SMC 20% between "C" and copper
	with Polyester Resin	80% of glass adhered to SMC 20% between "C" and copper
Key Epoxy E-12	Plain	100% adhesion of glass
	over 44410	90% adhesion of glass 10% between E-12 and 44410
PPG 44498	Plain	100% cohesive failure in 44498
	with Polyester Resin	100% between 44498 and copper
PPG 44498 over 44410	Plain	100% between the two paints
	with Polyester Resin	100% between the two paints

TABLE 8 - SMC - Glass Preliminary Tests-Quantitative Test Results (Room Temperature)

TYPE OF TEST	SYSTEM	MAX. STRESS	FAILURE MODE
Tensile	44410 Paint, plain	1170 psi	80% SMC/paint 20% cohesive paint
	44410 Paint, plain	1180 psi	70% SMC/paint 30% cohesive paint
	"C" Paint, plain	1400 psi	95% cohesive paint 5% SMC/paint
	"C" Paint, plain	1090 psi	95% cohesive paint 2% Paint/copper 2% Silver/glass 1% SMC/paint
	Key Epoxy E-12	1710 psi	75% within SMC 25% within glass
	Key Epoxy E-12	1830 psi	90% within SMC 10% within glass
Interlaminar Shear	44410 Paint, plain	1190 psi	90% Glass/fixture 5% Copper/paint 5% Paint/SMC
	44410 Paint, plain	1580 psi	70% Paint/SMC 30% Copper/paint
	"C" Paint, plain	1480 psi	60% Glass/fixture 25% Copper/paint 15% Cohesive/paint
	"C" Paint, plain	1530 psi	90% Glass/fixture 10% Glass/silver
	Key Epoxy E-12	1420 psi	85% Glass/fixture 15% Glass/silver

better adhesion in the tensile tests and comparable adhesion in the shear tests. It was decided to mold the next series of full size reflectors using the E-12 epoxy coating.

The answer to the second question is difficult to determine because of inherent differences between molding test pieces and molding full size panels. As mentioned earlier, the initial concept was to better understand adhesion between coated glass and SMC, and this result was achieved. Additional test pieces were molded later in the program when another adhesive showed good molding properties. Results of tests performed on this adhesive, also an epoxy base, will be discussed later in this report.

3.0 MOLDING OF TROUGH PANELS

The molding of the trough reflector panels can be broken into three distinct efforts. The first set of moldings familiarized us with the molding procedures and the types of problems to be expected in molding glass directly with SMC. The second effort was to evaluate the effects of slower closure and slower pressure build up by moving the die to a different press. The third effort was to test the adhesion properties of a different epoxy coating with a slightly modified SMC formulation. The third effort proved to be a successful attempt at co-molding glass and SMC.

3.1 INITIAL MOLDING EFFORT

The first trough panels were molded without glass to determine the charge pattern and to tryout the die. The initial charge pattern covered about 90% of the molding area with strips of SMC near the ribs and bosses to provide fill in those areas. The charge pattern was changed later to cover approximately 60% of the molding area with pads of SMC near the bosses to provide greater flow and a better quality panel.

After charge pattern tryout, a sheet of chemically strengthened glass was preheated at 250°F and placed in the mold. The charge pattern was placed on top and pressure applied for three minutes. When the press was opened the SMC had stayed on the rib (upper) side of the die. However, the glass did not adhere to the SMC and remained, unbroken, in the bottom. Encouraging signs on this first panel were essentially 100% rib and boss fill-out and an even edge of SMC around the periphery where the glass was located.

The same sheet of glass was again used, this time coated with a polyester resin which is the same resin as used in the SMC. The same charge pattern and molding pressures were used. This part showed relatively good adhesion between the glass and the SMC.

At this point some of the tests with flat, sample size mirrors as described in the SMC/Glass Adhesion part of the report were performed to get a better feel for the adhesion capability of various coatings. The molding of full size parts continued with E-12 epoxy coated glass and polyester resin coated glass, both of which provided promising results in the preliminary SMC/Glass adhesion tests. The following items were noted, although with varying degrees from panel to panel:

- Gaseous bubbles entrapped between the glass and SMC
- Delamination of the silver and glass

- Non-flushness of glass and SMC around the perimeter
- Tendency of panel to stay in bottom half of die
- Glass breakage in the mold

Figure 27 shows some of these problem areas. It was thought that one problem with the adhesion between the glass and SMC was possibly due to the creation of a vacuum between the glass and the bottom mold half. If the vacuum can be released before and during the upstroke of the ram, the glass and the SMC would not have a tendency to be pulled apart. To alleviate the apparent vacuum problem, six holes were drilled in the bottom mold half. A 0.50" diameter hole was drilled from the bottom to within one inch of the parabolic surface. A 0.25" diameter hole was then drilled through the 0.50" hole to within 0.25" of the mold surface. A 0.035" hole was then drilled from the top surface down through to the 0.25" hole. A diagram showing the location of the holes is given in Figure 28.

Aluminum sheets, the same size as the mirrored glass sheets, were then molded with SMC to check the function of the vacuum release holes and to gain confidence in glass placement and press operation. After the molding with aluminum, four sheets of painted mirrored glass were molded with SMC. The first two moldings used uncatalyzed polyester resin coated glass sheets, both of which survived the molding operation. Both panels showed non-flushness of the glass and SMC surfaces in the corners. The second molding showed large areas of silver delamination. The third and fourth glass sheets were coated with an epoxy E-12 coating over the 44410

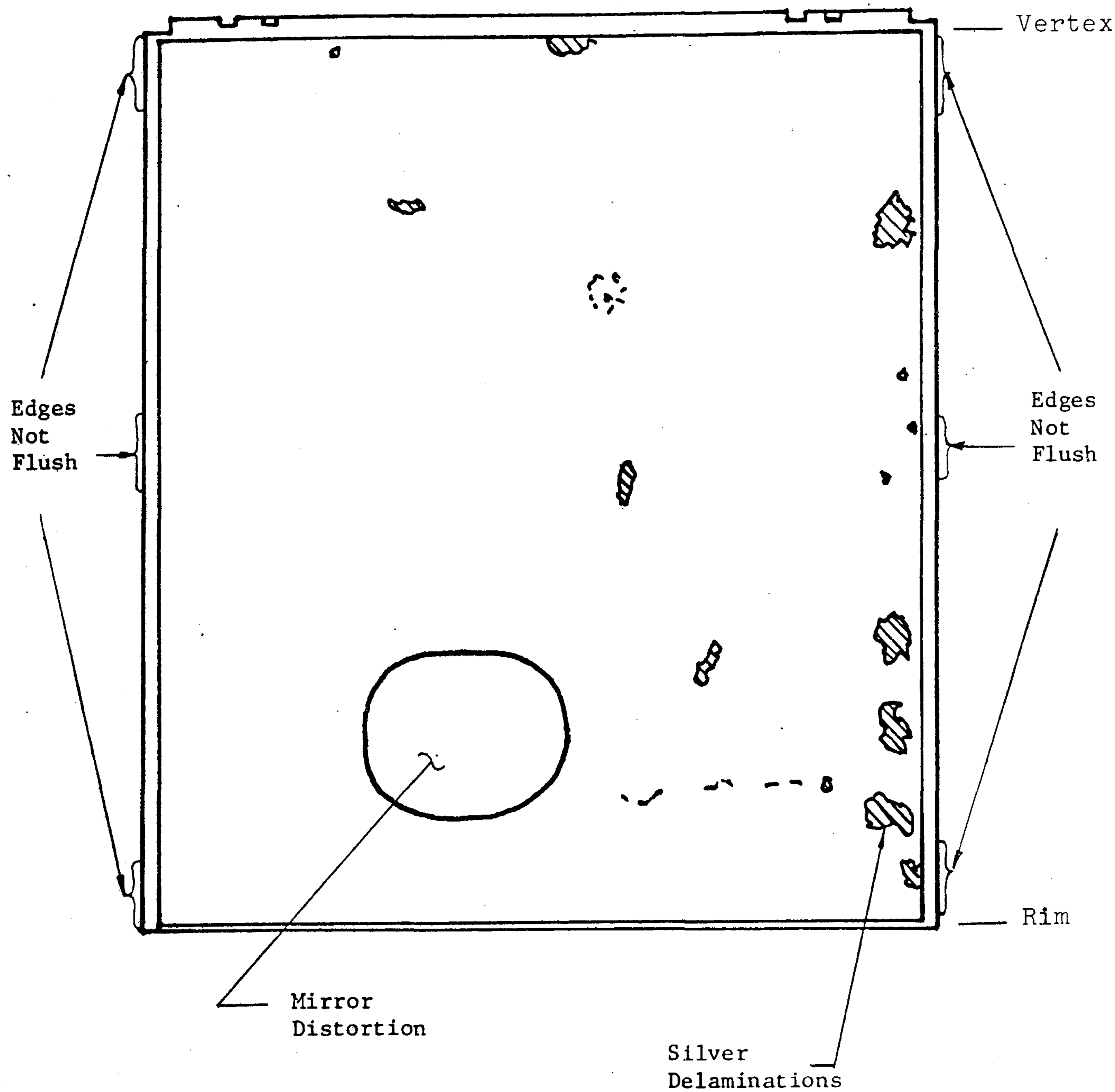


Figure 27. Molded Panel-Typical Problem Areas

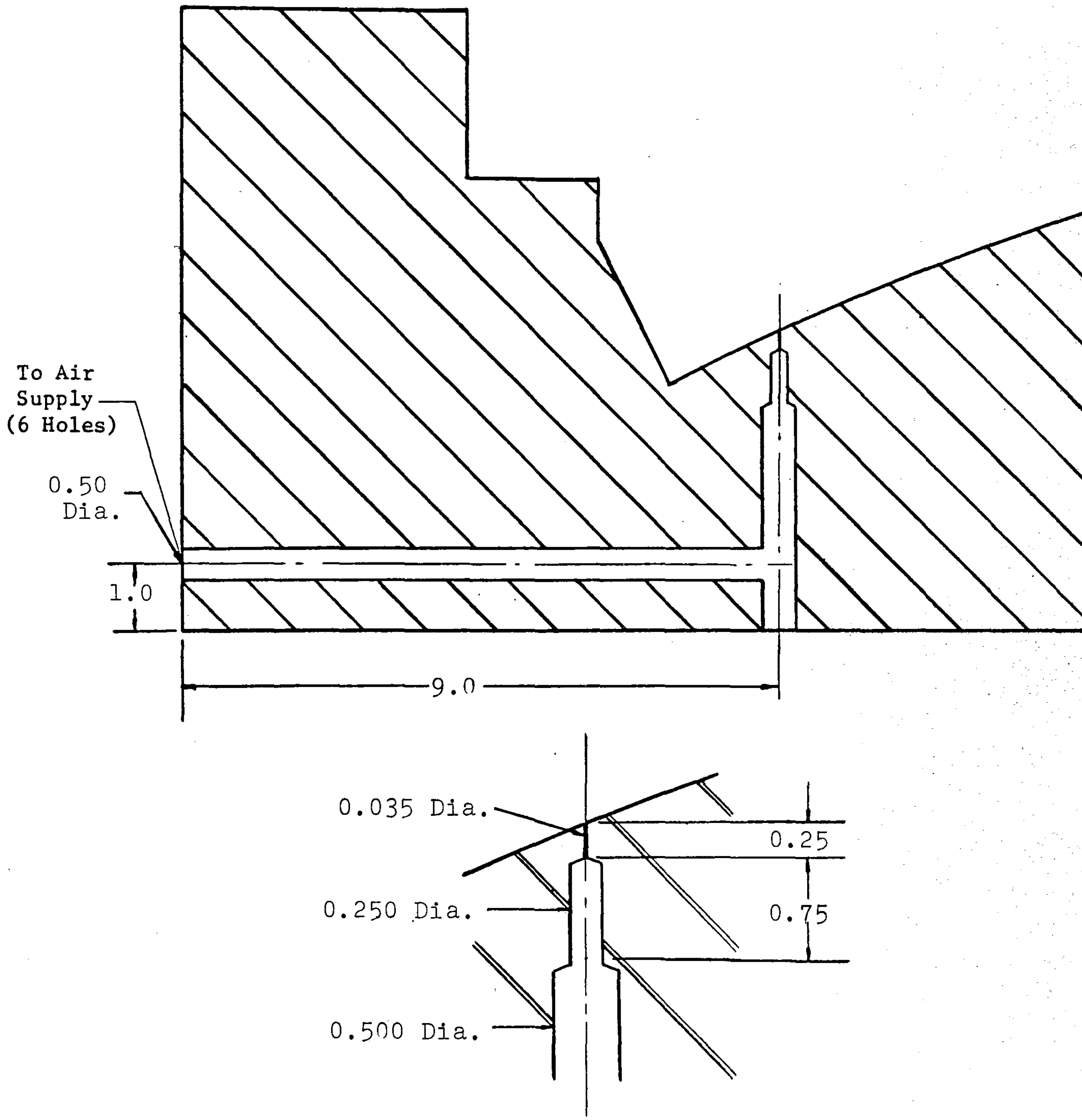


Figure 28. Vacuum Release Holes

paint. The third glass sheet diced in the mold, apparently due to a piece of dirt in the bottom surface. The fourth glass sheet survived the molding operation, although fill-out was incomplete on one rim corner. No silver delamination was noticed on this panel.

3.2 SECOND MOLDING EFFORT

At this point it was decided to move the die to a press used in production SMC molding. The first press, used in research and development projects, did not provide the closure rates and pressure build-up rates usually found in production presses. The second and subsequent molding operations with the 1m x 1m panels were conducted at Budd Co.'s Carey, Ohio production facility.

Although the vacuum release holes functioned properly, they did not provide conclusive evidence that if the ram opening was slowed more the adhesion problem could be solved. The gaseous bubbles seemed to be caused by air entrapment with a possible solution being to reduce the charge pattern coverage to allow greater flow of the SMC to push the air out in front of it. The glass breakage in the mold could be reduced by careful cleaning and placement.

After molding panels with slower closing and opening, the same results occurred as with the previous moldings; that is, the adhesion between the glass and SMC was poor and areas of glass-silver delamination were evident. Both a rigidized resin system SMC, as was used in the first moldings, and a flexibilized resin system SMC was used in this effort. A good flow SMC material is needed for complete mold fill-out. After a molding series which did not achieve the desired success, it was decided to re-evaluate the molding procedure, material flow ability, factors affecting SMC to paint adhesion, and factors affecting glass to silver adhesion.

3.3 THIRD MOLDING EFFORT

The third molding effort differed from the first two efforts in two ways. First, a coating consisting of a flexible epoxy resin was used on the back surface of the glass in an attempt to increase adhesion and decrease silver/glass delamination. Second, a flexibilized resin SMC material with a higher flow was used to achieve complete mold fill-out.

The coating over the existing protective paint on the silvered mirror required several major characteristics. It had to have adhesive strength at 300°F; it had to adhere to the paint and provide protection to the silver and copper layers; and it had to be adhered to by the SMC during molding. A Sandia development effort which included lap shear tests at 300°F investigated and evaluated several potential coatings. The coating finally selected was a mixture of 80.0 parts by weight of Shell Chemical Co. Epon 828, 20.0 parts by weight of Ring Chemical Co. Versamid 140, and 15.0 parts by weight of B.F. Goodrich Co. Hycar ATBN. Two methods, paint rollers and a wooden tongue depressor, were used to apply the coating under non-controlled conditions over the painted side of the mirrored glass. The coating was then cured for 30 minutes at 200°F. The cured coating had small circular discontinuities or small circular areas approximately 1/4" diameter with a very thin coating. The coating discontinuities could be seen in the molded panel on very close inspection.

The SMC material used in this third molding effort was modified for higher flow by increasing the polyester resin to filler ratio in the resin mix by approximately 3% to 4%. The glass fiber content remained 40% by weight.

The trough panels molded with the coating on the glass and the modified SMC achieved the required adhesion between the glass and the SMC without silver-glass delamination. The glass and SMC front surfaces are flush around the entire periphery of the panel. The gaseous bubbles were decreased by using the higher flow SMC which allowed for a smaller area charge pattern which pushed air out of the mold instead of trapping it. Glass breakage was reduced by extra care and cleanliness of the mold prior to placement of the glass in the mold.

This final molding effort proved to be a success at co-molding reflective glass and SMC into parabolic trough panels.

4.0 ACTUAL MATERIAL PROPERTIES

A 40% glass content rigidized polyester SMC was used on the first two molding efforts while a 40% glass content flexibilized polyester SMC was used on the third molding effort. Published data sheets indicated that the flexibilized resin SMC would provide the same strengths and the same thermal expansion coefficient as the rigidized resin SMC; however, the tensile and flexural moduli were expected to be 10% to 15% less, although still remaining above the 1.5 million psi required level. Tensile tests and thermal expansion coefficient tests were made on flat plaque molded parts. Flexural tests and glass fiber content tests were performed on both flat plaque parts and trough panel moldings.

A summary of the properties for the rigidized resin SMC molded in flat plaques is presented in Table 9. Selected properties for samples taken from a 1m x 1m molded panel are summarized in Table 10.

Flexural and tensile tests were also performed on the flexibilized resin SMC used in the third molding effort. Samples were cut from a molded flat plaque as shown in Figure 29 and also from a molded trough panel as shown in Figure 30. The results indicate that the strengths and moduli are averaging the expected values. Results are shown in Tables 11, 12,and 13.

5.0 PANEL INSPECTION

Two trough panels fabricated in the second molding effort were mechanically inspected using a digitizing machine, which for a given X and Z coordinate determine a Y value as defined by the coordinate system shown in Figure 31. The two one meter square trough panels were assembled into a one meter by two meter rim to rim panel for this inspection. The center line of the transverse axis is arbitrarily defined by Z = 50.000". and the center line of the longitudinal axis is arbitrarily defined by X = 100.000". For each

TABLE 9. Properties of Rigidized Resin SMC - 40% Glass Content, Flat Plaque Moldings

Tensile:	σ =	14,215 psi
	E =	2,192,200 psi
Flexural:	σ =	29,417 psi
	E =	1,692,200 psi
Material Content:	Resin -	27.8% by weight
	Filler-	30.4% by weight
	Glass -	41.8% by weight

TEC: 8.00 x 10^{-6} in/in/^{O}F average from 0^{O}F-200^{O}F

TABLE 10. Selected Properties of Rigidized Resin SMC - 40% Glass Content, 1m x 1m Trough Panel Molding

Flexural:	σ =	26,635 psi
	E =	1,510,000 psi
Material Content:	Resin -	27.0% by weight
	Filler-	30.6% by weight
	Glass -	42.4% by weight

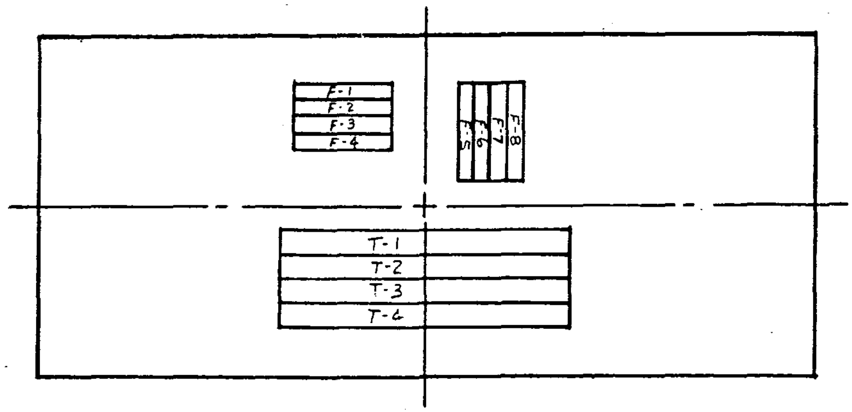


Figure 29 Tensile and Flexural Sample Location - Flat Plaque-Flexibilized Resin SMC

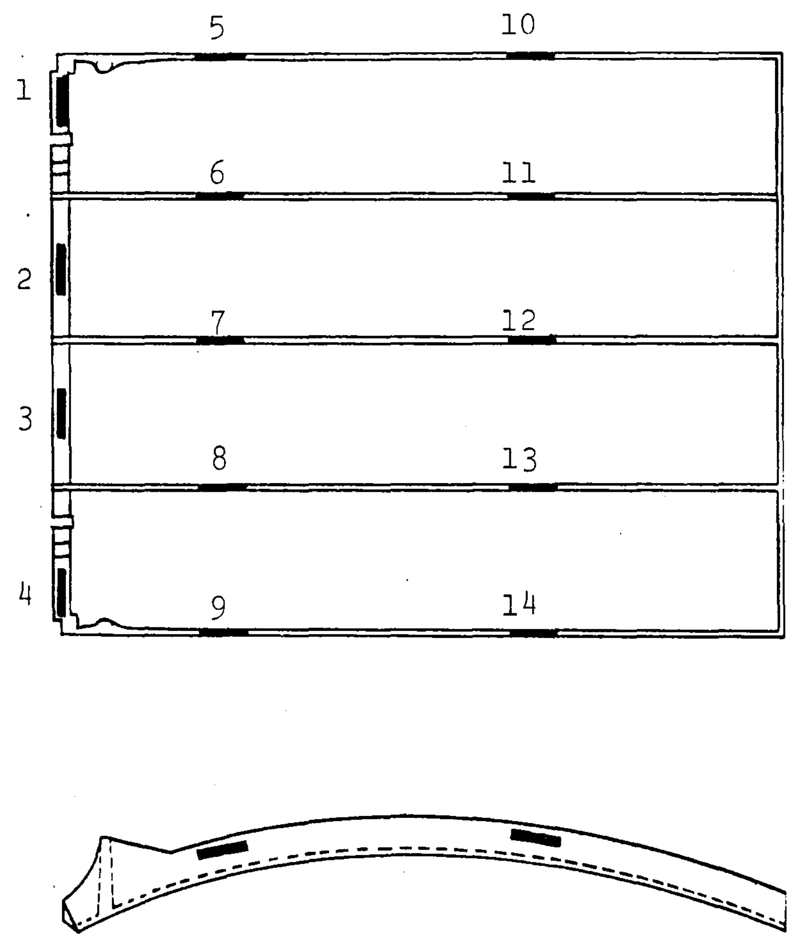


Figure 30 Flexural Sample Location - Trough Panel-Flexibilized Resin SMC

TABLE 11 - Tensile Test Results-Flexibilized Resin SMC, 40% Glass Content

	σ_y (psi)	σ_{ult} (psi)	E (psi)
$\bar{x}$	11,230	16,940	1,783,300
s	1,016	1,033	125,700
cov	9.0%	6.1%	7.0%
n	4	4	4

TABLE 12 - Flexural Test Results-Flat Plaque Flexibilized Resin SMC, 40% Glass Content

	σ_{Max} (psi)	E (psi)
$\bar{x}$	26,650	1,536,400
s	3,470	146,100
cov	13.0%	9.5%
n	8	8

TABLE 13 - Flexural Test Results-Trough Panel Flexibilized Resin SMC, 40% Glass Content

	σ_{Max} (psi)	E (psi)
$\bar{x}$	28,970	1,482,000
s	8,020	296,800
cov	27.6%	20.0%
n	14	14

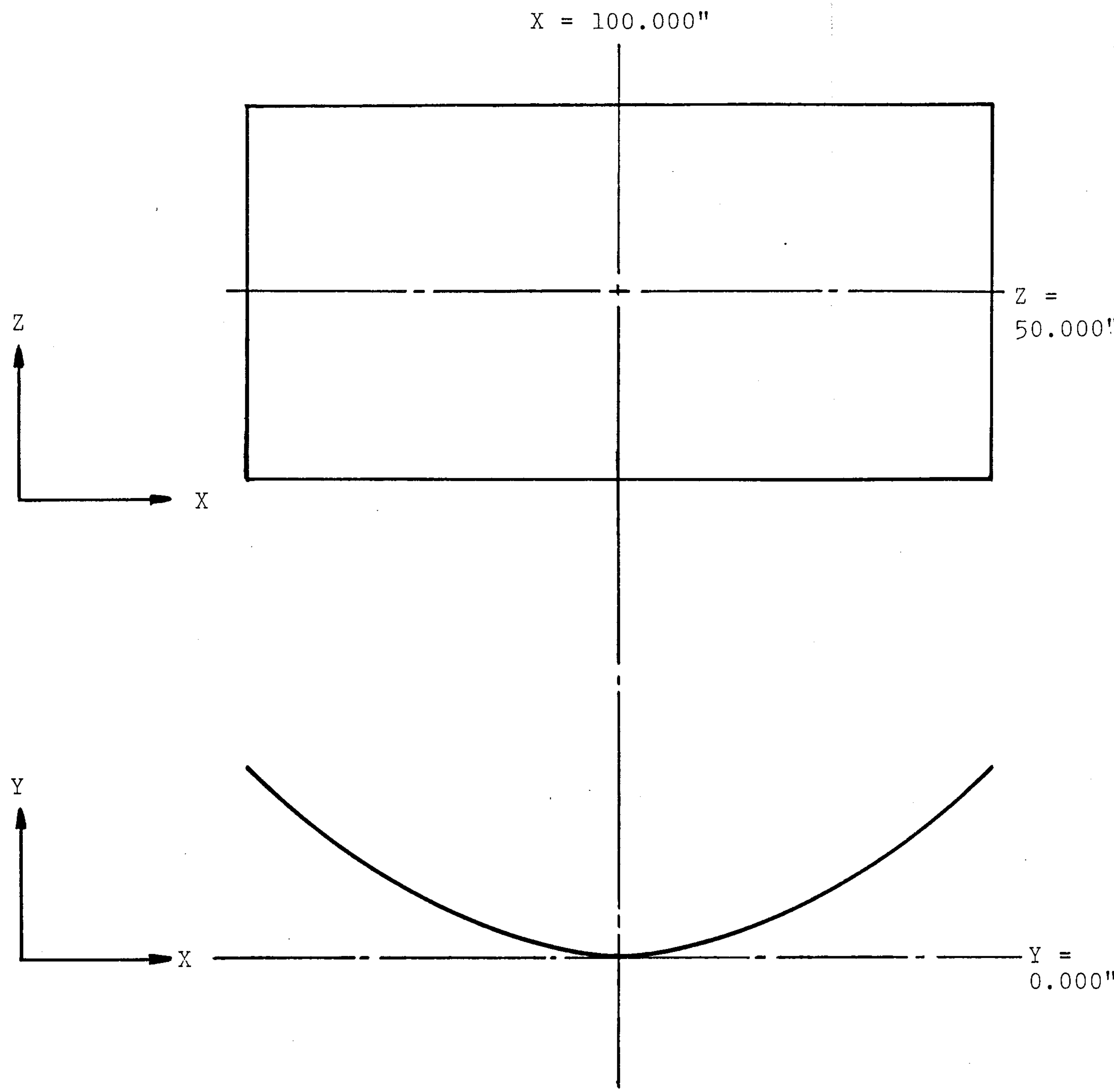


Figure 31. Inspection Coordinate System

Z value, which ranged from 32" to 68" in increments of 4", thirteen X values were used and the associated Y value determined. This represents a total of 130 points that were measured over the entire panel surface.

A computer program was developed that will define a best fit parabolic equation trough a number of points. For each Z value, thirteen (X, Y) values were inputed to the computer to determine the best fit parabolic equation through those thirteen points. This procedure was used for each of the ten Z values. Appendix B shows the results of the analysis for each of the ten Z values. Each printout produces the following:

- Z Value
- X Value
- Y Value, which is the inputed value
- Y Estimate, which is the computer calculated value for the best fit equation through that particular (X,Z) coordinate
- Residual, which is Y values minus Y estimate
- Focal Length
- Coordinate of the focal point
- Correlation coefficient

Results of the analysis show that the focal length varied from 19.34" toward the center of the panel to 19.50" toward the outer edges. It is believed this is due to the crowning of the panel because of the thermal expansion mismatch between the glass and the SMC. That is, relative to the center of the panel the outer edges are opened, which would give a greater focal length.

It is also believed that the attachment along the vertex is critical in obtaining the correct focal length because of a tendency for two halves to open at the vertex. Also, with the boss attachment points relatively close to the vertex, even a small error in positioning the bosses results in compounded error at the rims due to a cantilever effect. Results in another contract, Sandia 74-9133, indicates that the focal length of two halves when bonded and riveted at the vertex and rigidly attached to an accurate fixture averages 19.02".

An average focal length for the entire panel was also determined and is included in Appendix B. The average focal length is 19.405" with the focal point located at (X,Y) = (100.000, 19.429). The equation of the best fit parabola is:

$$(X-100.000)^2 = (4)\ (19.405)\ (Y+19.405-19.429)$$

$$(X-100.000)^2 = 77.620\ (Y-.024)$$

An interesting fact noted during the computer analysis is that the focal length and focal point coordinates from the left half of the parabola cannot be averaged with the focal length and focal point coordinates from the right half to obtain the focal length and focal point coordinates of the entire parabola. For example, for Z = 60.000", Table 14 shows that the focal length for the full parabola is less than the focal lengths for each half. This fact is possibly due to the fitting of a best fit equation through the data points and the mathematics of the problem does not allow for simple averaging. Averaging should not be used.

Left Half		Right Half		Full Parabola	
Focal Length	Focal Pt.	Focal Length	Focal Pt.	Focal Length	Focal Pt.
19.423	(100.049,19.430)	19.427	(99.962,19.446)	19.385	(100.000.19.406)

TABLE 14 - LEFT, RIGHT AND FULL PARABOLA DATA

6.0 MOLDING OF SMC LIP AROUND GLASS

Chemically strengthened glass and SMC were molded together in a flat plaque die to determine if a lip of SMC could be successfully molded around and under the glass surface without breaking the glass, Figure 32. Variables included thickness of the lip and length of glass overhang. Combinations were:

- .060" thickness, .125" overhang, two sides
- .125" thickness, .25" overhang, two sides
- .060" thickness, .25" overhang, four sides
- .040" thickness, .25" overhang, four sides

All combinations attempted were successful in that a clearly defined lip of SMC was molded under the glass surface without breaking the glass. This SMC lip provides a mechanical locking device to hold the glass in place and gives an added safety feature to keep the glass and SMC together. Subsequent molding of vertex to rim trough panels has shown that the SMC lip is applicable to large curved panels.

7.0 PANEL MODIFICATION

The original concept for the assembly of the vertex to rim

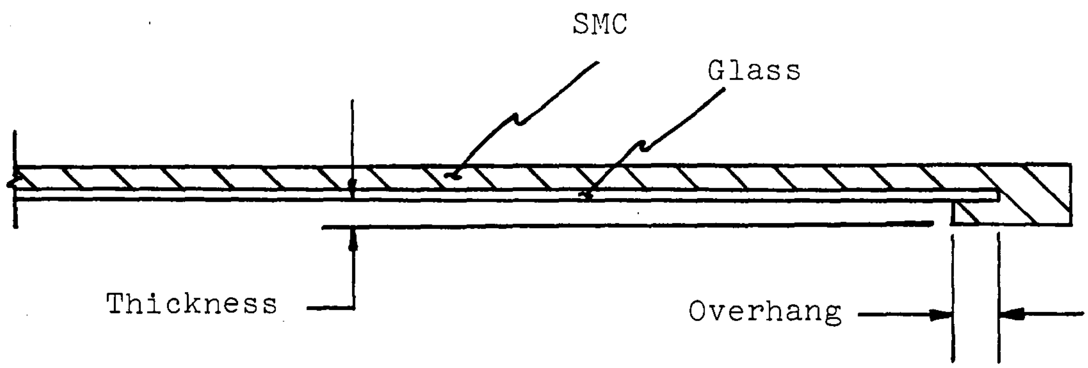


Figure 32. Molding of SMC Lip Around Glass

SMC panels was to join two panels at the vertex and mount this assembly directly to a ten inch diameter torque tube. But because of the desire to keep various trough panel designs adaptable to a common strongback, this concept was changed to account for different attachment points. The assembly of two vertex to rim panels into one rim to rim panel includes the following:

- Remove the boss areas on the molded panels
- Bond and rivet the vertex coamings
- Bond and rivet steel doubler plates between the panels to provide additional strength across the vertex joint
- Bond and rivet steel hat section parts with floating attachment nuts to provide a mounting feature

Figure 33 shows the two panel assembly, of which two were assembled to develop the necessary fixtures and procedures.

8.0 INVESTIGATION OF EPOXY COATING

The successful molding effort was due in large part to the use of the epoxy resin mix that provided the required adhesion of the glass to the SMC. However, this mix was rather thick and not easily applied to the back of the glass. The purpose of the coating investigation at Budd was to determine a method of applying the mixture to the protective paint of the chemically strengthened glass mirrors so that the coating is thin, uniform, easily applied and similar in properties to the successful mixture. The method of approach was to perform brushing and spraying tests of

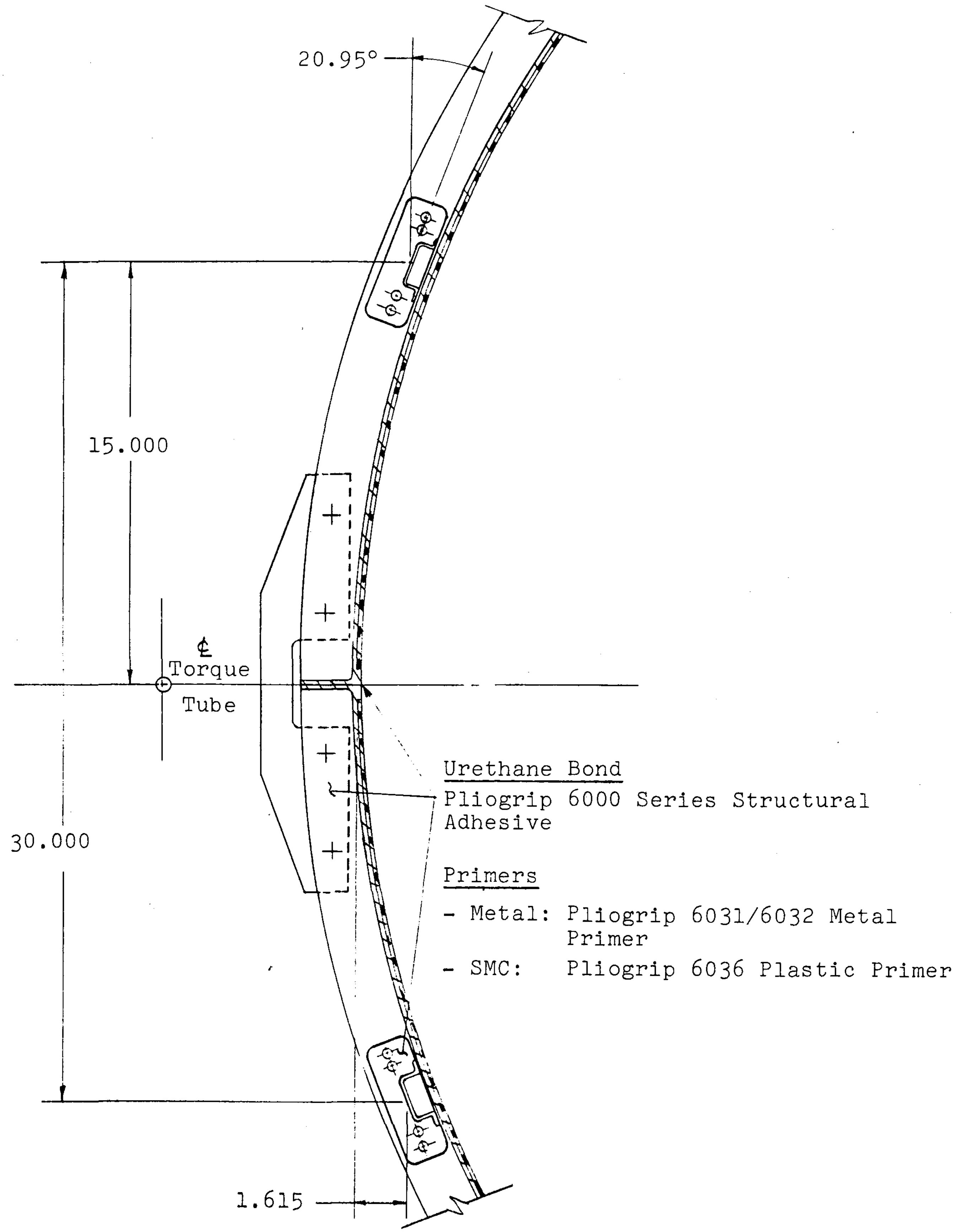


Figure 33. Two Panel Assembly

various blends using reactive diluents and solvents, overlap shear tests including room and high temperature testing, molding with SMC, and tensile and shear tests of molded SMC/glass samples at room and high temperature.

Table 15 shows the results of one inch wide, one inch overlap shear specimens of ten different mixtures tested at room temperature and 300°F. The butyl alcohol/toluene mixture (#8) was chosen as the best candidate at the time. Additional input was received from Sandia indicating that previous epoxy based adhesives with toluene may present long-term adhesion problems. The decision was made to try Methyl Ethyl Ketone (MEK) as a solvent.

Results of spraying tests to acquire a smooth surface indicated that the mixtures required filtering to remove solid particles of epoxy. Both the butyl alcohol/toluene mixture and the MEK mixture provided smooth surfaces after filtering.

Both mixtures were sprayed on mirrored glass, molded with SMC, and tested to obtain tensile and shear values at room temperature and 300°F. Results are shown in Table 16. Although the butyl alcohol/toluene mixture gave slightly greater high temperature properties than the MEK mixture, it was decided to use the latter because of concern over the long-term toluene adhesion capability.

The procedure for coating of the mirrored glass is as follows:

- Clean the back painted surface with a clean cloth damp with methylene chloride. Wipe the painted surface at least twice for complete cleaning.

TABLE 15 - Epoxy Coating Investigation
Overlap Shear Test Results

Mixture No.	Strength (psi) Room Temperature	300°F
1	1833	143
2	1000	140
3	830	128
4	350	0
5	1680	0
6	1700	67
7	55	0
8	1860	76
9	120	0
10	134	5

Mixture Identification - Each mixture, except #7, is a combination of the basic mixture #1 plus additives to make the basic mixture sprayable.

(1) The basic mixture is: 80g Epon 828
20g Versamid 140
15g ATBN

(2) Basic mixture plus 17g Butyl Glycidyl Ether (BGE)

(3) Basic mixture plus 17g BGE plus 2 drops Airout

(4) Basic mixture plus 21g Toluene
21g Methyl Isobutyl Ketone
21g Cellosolve
3g Cyclohexanol
2 Drops Airout

TABLE 15 - (Continued)

(5)	Basic mixture plus	30g Methyl Isobutyl Ketone 33g Toluene 3g Cellosolve 3 Drops Airout
(6)	Basic mixture plus	63g Methylene Chloride 3g Cyclohexanol 3 Drops Airout
(7)	Finnaren & Haley Epoxy-Polyester Coating System ONLY	
(8)	Basic mixture plus	33g n Butyl Alcohol 30g Toluene 3g Cyclohexanol 3 Drops Airout
(9)	Finnaren & Haley Epoxy-Polyester Coating sprayed on and cured. Coating #8 sprayed on top of F & H.	
(10)	Basic mixture plus	33g n Butyl Alcohol 30g Toluene 3g Cyclohexanol .33g Silicone Surfactant

TABLE 16 - Epoxy Coating Investigation

Flat Wise Tensile and Interlaminar Shear Test Results

Coating	Application	Temp	No. of Samples	Average Strength	Failure
80, E-828 20, V-140 15, ATBN 11, BGE 22, MEK	Sprayed	70°F 300°F	1 1	1129 psi 188 psi	Between fixture and SMC 100% Cohesive
80, E-828 20, V-140 15, ATBN 33, Butanol 33, Toluene	Sprayed	70°F 300°F	1 2	767 psi 230 psi (229,231)	80% SMC/Coating 20% Within SMC 100% Cohesive
None	-	300°F	1	71 psi	SMC/Paint Paint/Copper
80, E-828 20, V-140 15, ATBN 11, BGE 22, MEK	Sprayed	70°F 300°F	1 2	1264 psi 74 psi (52,96)	Between Fixture and SMC 100% Cohesive
80, E-828 20, V-140 15, ATBN 33, Butanol 33, Toluene	Sprayed	70°F 300°F	1 1	1707 psi 189 psi	Between Fixture and SMC 100% Cohesive
None	-	300°F	1	60 psi	SMC/Paint Paint/Copper

- Prepare the adhesive as follows:

Epon 828	-	2000 g (56.6%)
Versamid 140	-	500 g (14.1%)
ATBN	-	375 g (10.6%)
MEK	-	660 g (18.7%)

  Degas

  Using four paint filters, pour half of the above mixture into 2 quart spray gun. Cover the remaining mixture to prevent solvent evaporation.

- Spray the cleaned sheet in a horizontal position. The second coat is to be sprayed 90° to the first coat. The third coat is to be sprayed 90° to the second coat. The cured coating is to be 0.009" nominal thickness.

- Cure the sprayed sheets for 1 hour at room temperature plus 1 hour at 240°F.

9.0 COST

A production quality steel mold for producing a 1m x 2m panel would cost in the area of $400,000. This cost does not include core pins or slides for locating the glass in the mold although such items may be required for accurate glass placement. The detailed design of such a locating system would dictate its additional cost to the mold. Mold delivery would be approximately

38 weeks with an additional 10 weeks for mold tryout, fabrication of samples and the beginning of production. Total time from mold order to production is approximately 48 weeks. A 1m x 1m production quality steel mold would cost approximately $165,000, not including core pins or slides for glass placement. Mold delivery on the half panel tool would be approximately 28 weeks with an additional 10 weeks for tryout and sample fabrication.

Sheet molding compound materials with a 40% by weight glass fiber content are commercially available in the price range of $0.80 to $0.90 per pound in production quantities. The 1m x 1m panel consists of about 25 pounds of SMC. With an optimized panel design and production tooling the weight of SMC for a 1m x 2m panel could be reduced from 50 pounds (2x25 pounds) to approximately 45 pounds. Thus, direct material cost, not including wastage and scrap rate, would range from $36.00 to $40.50 per 1m x 2m panel, or $1.67 to $1.88 per square foot of aperature area.

Current automotive parts, such as a hood, of the same general size as the 1m x 1m panel, are being molded for approximately $2.00 to $2.50 per pound, which includes direct material, direct and indirect labor, press burden rates, overhead, and about a 6% allowance for scrap. This price does not include the price of the glass and a probable higher scrap rate due to glass breakage, both in handling and during molding. The molded cost per pound of SMC for the 1m x 2m panel is expected to be in the $2.00 to $2.50 price range also. The molded cost per square foot of aperature area would be $4.18 to $5.23.

Two other items, one standard and one non-standard, are required for solar panel molding. A glass preheat oven, not required for standard SMC molding, is necessary for the reasons outlined in the Fixture Design and Fabrication section of the report. A check gauge is also required to verify the parabolic contour dimensionally (as opposed to optically). The cost of these two items would be approximately $10,000 to $15,000.

Chemically strengthened glass, more expensive than annealed glass, was found to be necessary for successful molding of solar panels. The estimate of the cost of high volume production for the glass fabrication, the strengthening process, and the silvering process is in the range of $3.00 to $3.50 per square foot.

Other capital expenditure items may be considered for solar panel molding. Although increasing capital investment initially, these items may prove cost effective in the long run by reducing material waste and increasing daily output. An automatic glass handling device, automatic SMC material cutting and loading into the press, and automatic unloading of the panel fall into the category of such items that can reduce cost over production quantities. Since manual operation is still the norm in SMC molding and because the above items would require devices specifically tailored to solar panel molding, costs are difficult to estimate.

In summary, cost information on producing SMC solar panels has been provided although a specific cost is difficult to calculate because of unknown variables in production glass prices and the molding parameters not able to be completely defined in this prototype development effort.

10.0 CONCLUSIONS

The results of this development effort have established that solar reflector panels can be produced by high volume, low cost production methods typically used by the automotive industry. Several problems encountered during this project required new materials and/or new processes in order to achieve successful co-molding of the strengthened glass and the SMC into an integral structural reflector panel. The co-molding of these two materials eliminated a separate bonding operation (of the mirror to an SMC molded structure) and provided an environmental seal for the silver coating on the molded surface of the glass. Co-molding also offers the potential for reducing the overall cost of the panels.

The major factors in this project included:

- design of the die
- use of chemically strengthened glass
- development of a coating for the mirrors
- use of an SMC material with appropriate flow and strength characteristics
- execution of good molding practices

The design of the compression molding dies is critical in that it must be of the proper focal length (curvature) to produce a cool molded part of the design focal length. Large temperature changes (300°F to 70°F) and thermal expansion mismatch considerations make this a real challenge. Evaluation of the parts produced under this contract are expected to provide information to aid in die design to produce the specified focal length of molded parts. This area will require additional correlation.

The die must also present a smooth, accurate surface to support the glass during molding. Since no ejection pins can be used against the face of the glass, the die design must be special to assure that the part stays on the proper (ribbed) half of the die, yet be easily ejected. The ejection action must push uniformly on the part to avoid distortion of the part when it is at molding temperature when the SMC/glass interface adhesion may be most vulnerable.

The chemically strengthened glass mirrors are indispensible to this fabrication concept. Other types of glass would probably not survive the molding conditions. The chemically strengthened glass can be produced and silvered as a flat sheet using existing production facilities and then elastically formed to contour during molding.

A protective coating was found to be necessary over the regular mirror paint. This coating was necessary to provide good adhesion of the SMC to the mirror without producing delamination within the multiple layers of the reflective glass (silver, copper, and paint). The delamination effects encountered in early molding were eliminated by the coating which provided the required adhesive strength at molding temperature. A suitable method of appliation of the coating was developed. The long term effectiveness of the coating is still to be determined; preliminary results are excellent.

One of the major areas still needed in solar reflector development is that of a good protective coating for the silver and copper on glass mirrors. This coating should be in lieu of the paint presently used throughout the mirror industry. The required characteristics for this coating can be specified for a development effort.

Environmental testing is underway on the molded panels. Preliminary evidence indicates that some silver degradation is occurring after extended exposure to high temperatures (120^{o}-160^{o}F). The cause of this degradation is unknown; the molding temperature of 300^{o}F is one of several suspected factors. Investigations continue at Sandia.

The SMC materials used in this development effort demonstrated that proper material selection is very important in achieving good flow, complete fill and required material properties. Flow characteristics are particularly important with ribbed structures, as well as the problem of poor thermal conductivity of glass inhibiting heat flow from the die to the SMC through the glass. Thermal expansion, strength, and modulus are important in the response of the panel to its outdoor environment.

Mounting features, such as molded bosses suitable for installation of threaded inserts, were established as appropriate methods of providing panel attachment to the collector framework. Bosses were successfully molded and insert installation techniques were developed. Pull out strengths of inserts were determined to have acceptable safety factors.

The success in fabrication of half parabola (vertex-to-rim) panels gives confidence that a full rim-to-rim panel with glass could also be molded, if strengthened glass panels of the proper size were available. Design of the rib structure for a rim-to-rim panel would require consideration of the torsional and deflectional stiffness requirements as well as the strength of the SMC material and rib depth which can be molded.

Molding operations with glass mirrors clearly showed a requirement for extra care in maintaining cleanliness of the mold face. The glass mirror is placed against the mold face and held there under molding pressure. Any grit, dirt, or other contamination under the glass can be expected to cause fracture of the glass. When strengthened glass fractures, it "dices" or fractures throughout into very small pieces. A fractured piece of glass will inevitably leave small particles which must be thoroughly cleaned out of the die prior to the next molding. The stringent cleanliness requirements will probably cause an increase in mold cycle time and, in the event of a fracture, in clean-up time. In addition, the mirrors must be preheated immediately prior to molding and transferred quickly to the press. Such operations are not typical in production SMC molding and will require more than normal manpower and facilities. Thus, the production rate of mirror panels may be expected to be slower than for current SMC auto parts.

Any future production molding of glass mirrors into SMC structures will require a method of automatic positioning of the preheated glass within the mold and its retention in the specified position during charge placement and molding. Simple aids were devised for this project and they functioned very well.

However, each sheet of glass was carefully placed by hand by two people and double checked after SMC charge placement. A more sophisticated, automated method of glass placement and retention should be a high priority in further development of SMC reflector panel structures.

11.0 RECOMMENDATIONS

The prototype reflector panels fabricated under this contract have shown the technical feasibility of co-molding chemically strengthened reflective glass with sheet molding compound into 1m x 1m vertex-to-rim parabolic panels. Additional development will be required before mass production would become feasible.

Future efforts will be required in the areas of: environmental evaluation of presently molded panels; die design to provide positive positioning of the reflective glass in the mold; protective coatings for the glass; SMC material correlation with structural analysis; investigation of long-term creep in SMC; design of an optimized 1m x 2m panel with integrally molded attachment points; and automated techniques for glass handling, SMC loading, panel demolding, and possible on-line optical inspection techniques.

References

1. "Structural SMC: Material, Process and Performance Review", Jutte, R.B., 33rd Annual Technical Conference, RP/SPI, 1978.

2. "Analysis/Design of Strip Reinforced Random Composites (Strip Hybrids)", Chamis, C.C. and Sinclair, J.H., Composite Materials in the Automobile Industry, ASME, 1978

3. "Mechanical Properties Characterization of an SMC R-50 Composite", Denton, D.L., 34th Annual Technical Conference RP/SPI, 1979.

4. "Carbon Fibers Add Muscles to Plastics", Theberge, J., Arkles, B., and Robinson, R., Machine Design, Feb. 7, 1974

5. "Reinforced RIM: Processing Know-How Progresses", Plastics Technology, Nov., 1978.

6. "The Case for Threaded Inserts", Viscio, D.P., Assembly Engineering, June, 1972.

APPENDIX A

INSERT PRODUCT LITERATURE

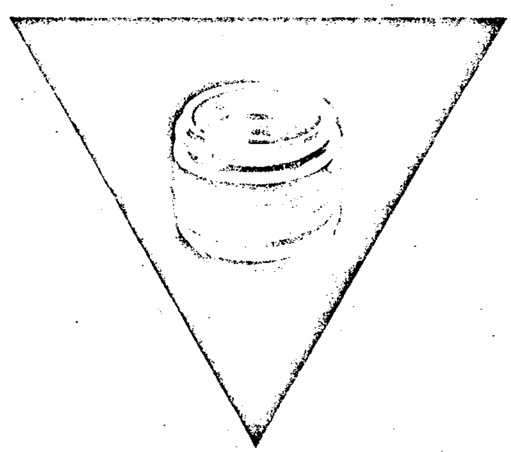
Repair and prevent stripped threads with

E-Z LOK

THREAD INSERTS

NOW AVAILABLE IN STAINLESS STEEL

Fast and easy to install
No special tools
of any kind required



E-Z LOK external threads are standard size and pitch to permit use of standard drills and taps. **No special tap sizes or installation tools are required.**

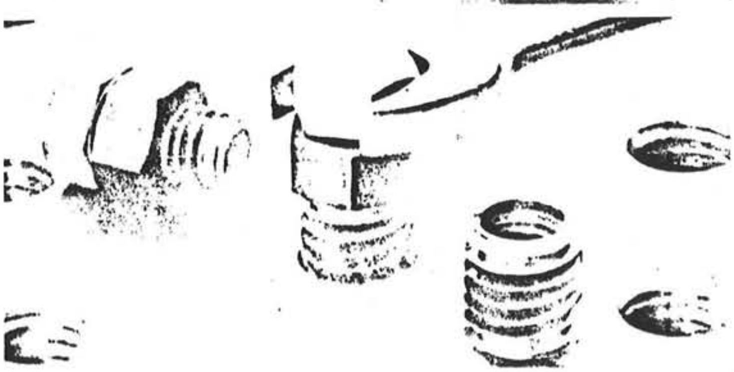
Use in:

magnesium • aluminum • cast iron • steel
copper • brass

Installation is easy as 1-2-3

1 Drill with standard drill.

2 Tap hole with standard tap.



3 Turn E-Z LOK home flush with bolt, stud or spark plug.

Automatic self-locking external thread with use-activated adhesive

E-Z LOK inserts will not back out or vibrate loose.

Immediately on installation, microencapsulated epoxy molecules begin to set, and the newly installed insert can be fastened to within minutes. The adhesive continues to cure overnight until completely set.

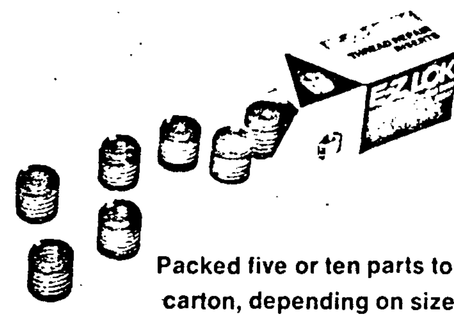
The adhesive seals against liquids and gases to pressures of 6,000 psi, and bonds to virtually all metals.

Easy Removal
Use a standard screw and bolt extractor to back out a damaged insert and then replace it with a new insert.

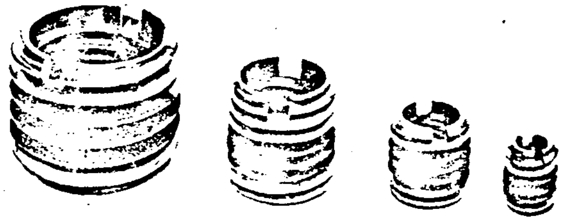
Removal is simply a matter of overcoming the resistance to torque-out which has been produced by the thread locking material.

E-Z LOK

THREAD INSERTS **are available in a wide range of sizes for machine screws, bolts, studs and spark plugs with coarse, fine or metric threads. Now in rust protective finished steel or 303 stainless, passivated.**



Packed five or ten parts to a carton, depending on size.



Use E-Z LOK Thread Inserts for: Jigs and Fixtures • Bolster Plates • Dies • Machine Tools • Metal Patterns • Farm Machinery • Engine Blocks • Parts Salvage • Stripped Threads in any material

	E-Z LOK PART NO.	INTERNAL THREAD	EXTERNAL THREAD	LENGTH	TAP DRILL SIZE	TAP SIZE	MINIMUM FULL THREAD DEPTH
COARSE THREAD SIZES	329-004	4-40	10-32	.250	5/32	10-32	9/32
	329-006	6-32	1/4-20	.280	7	1/4-20	11/32
	329-008	8-32	5/16-18	.290	F	5/16-18	7/16
	329-3	10-24	3/8-16	.406	5/16	3/8-16	15/32
	329-4	1/4-20	7/16-14	.437	23/64	7/16-14	1/2
	329-5	5/16-18	1/2-13	.484	27/64	1/2-13	9/16
	329-6	3/8-16	9/16-12	.515	31/64	9/16-12	19/32
	329-7	7/16-14	5/8-11	.656	17/32	5/8-11	23/32
	329-8	1/2-13	3/4-10	.656	21/32	3/4-10	3/4
	329-9	9/16-12	3/4-10	.656	21/32	3/4-10	3/4
	329-10	5/8-11	7/8-9	.687	49/64	7/8-9	13/16
	329-1018	5/8-11	7/8-9	1.125	49/64	7/8-9	1-1/4
	329-12	3/4-10	1-8	.781	7/8	1-8	7/8
	329-16	1-8	1-3/8-12	1.250	1-9/32	1-3/8-12	1-3/8
FINE THREAD SIZES	329-332	10-32	3/8-16	.406	5/16	3/8-16	15/32
	329-428	1/4-28	7/16-14	.437	23/64	7/16-14	1/2
	329-524	5/16-24	1/2-13	.484	27/64	1/2-13	9/16
	329-624	3/8-24	9/16-12	.515	31/64	9/16-12	19/32
	329-720	7/16-20	5/8-11	.656	17/32	5/8-11	23/32
	329-820	1/2-20	3/4-10	.656	21/32	3/4-10	3/4
	329-10F	5/8-18	7/8-9	.687	49/64	7/8-9	13/16
	329-1216	3/4-16	1-8	.781	7/8	1-8	7/8
METRIC THREAD SIZES	650-6	M6 -1.0	3/8-16	.406	5/16	3/8-16	15/32
	650-8	M8 -1.25	1/2-13	.484	27/64	1/2-13	9/16
	650-10	M10-1.50	9/16-12	.515	31/64	9/16-12	19/32
	650-12	M12-1.75	3/4-10	.656	21/32	3/4-10	3/4
	650-14	M14-2.0	7/8-9	.687	49/64	7/8-9	13/16
	650-16	M16-2.0	1-8	.781	7/8	1-8	7/8

METRIC INTERNAL / METRIC EXTERNAL

METRIC BOLT SIZES	450-3	M3-0.5	M6-1.0	6.5mm	5.1mm	M6-1.0	7.8mm
	450-4	M4-0.7	M8-1.25	7.5mm	6.9mm	M8-1.25	8.5mm
	450-5	M5-0.8	M8-1.25	7.5mm	6.9mm	M8-1.25	9.0mm
	450-6	M6-1.0	M10-1.5	10.5mm	8.6mm	M10-1.5	12.0mm
	450-8	M8-1.25	M12-1.75	12.5mm	10.4mm	M12-1.75	14.5mm
	450-10	M10-1.5	M16-2.0	17.0mm	14.0mm	M16-2.0	15.5mm
	450-12	M12-1.75	M16-2.0	17.0mm	14.0mm	M16-2.0	19.0mm
	450-16	M16-2.0	M24-3.0	20.0mm	21.0mm	M24-3.0	24.0mm
FOR 14MM SPARK PLUGS (12.7MM REACH)	750 14	M14-1.25	M18-1.5	11.5mm	15.5mm	M18-1.5	12.7mm

303 STAINLESS STEEL, PASSIVATED

COARSE THREAD SIZES	303-3	10-24	3/8-16	.406	5/16	3/8-16	15/32
	303-4	1/4-20	7/16-14	.437	23/64	7/16-14	1/2
	303-5	5/16-18	1/2-13	.484	27/64	1/2-13	9/16
	303-6	3/8-16	9/16-12	.515	31/64	9/16-12	19/32
	303-7	7/16-14	5/8-11	.656	17/32	5/8-11	23/32
	303-8	1/2-13	3/4-10	.656	21/32	3/4-10	3/4
FINE THREAD SIZES	303-332	10-32	3/8-16	.406	5/16	3/8-16	15/32
	303-428	1/4-28	7/16-14	.437	23/64	7/16-14	1/2
	303-524	5/16-24	1/2-13	.484	27/64	1/2-13	9/16
	303 624	3/8-24	9/16-12	.515	31/64	9/16-12	19/32
	303-720	7/16-20	5/8-11	.656	17/32.	5/8-11	23/32
	303-820	1/2-20	3/4-10	.656	21/32	3/4-10	3/4

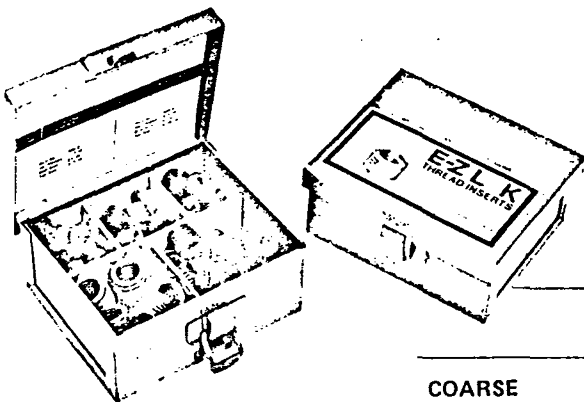
EXTRA HEAVY WALL

COARSE THREAD SIZES	335-4	1/4-20	1/2-13	.484	27/64	1/2-13	9/16
	335 5	5/16-18	9/16-12	.515	31/64	9/16-12	19/32
	335-6	3/8-16	5/8-11	.656	17/32	5/8-11	23/32
	335-8	1/2-13	7/8-9	.687	49/64	7/8-9	13/16
	335-10	5/8-11	1-8	.781	7/8	1-8	7/8

E-Z LOK

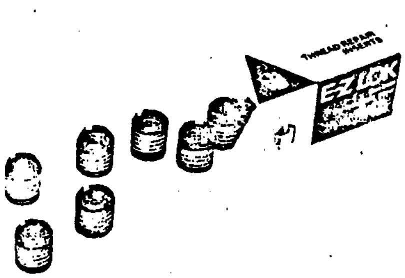
THREAD INSERT REPAIR KITS

- Quantities and sizes established from thorough analysis of demands of industrial, tooling, automotive, farm and heavy equipment users
- Packaged in heavy duty, welded steel box with hinged lid and snap lock
- Ideal for shop storage or carrying in tool box for field applications
- Speedy, convenient method for repairing a broad range of threaded hole sizes anywhere, anytime, in most any material

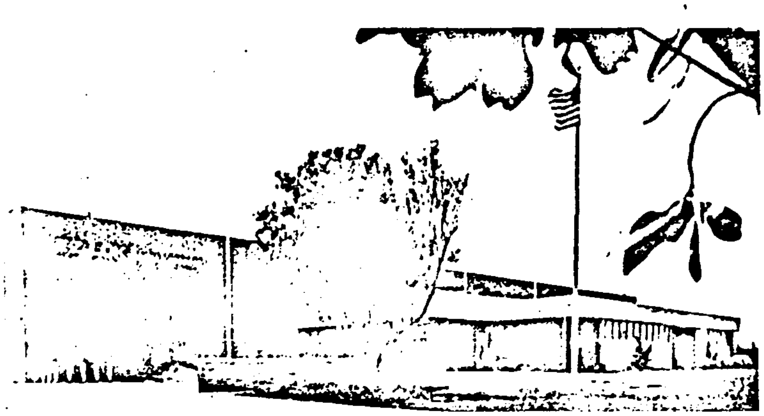


Convenient thread repair kits contain a selection of popular sizes of E-Z LOK thread inserts.

	KIT NUMBER	QUANTITY OF INSERTS	INSERT PART NUMBER	INTERNAL THREAD	EXTERNAL THREAD
COARSE THREAD #10 to 1/2"	EZ-C108	10	329-3	10-24	3/8-16
		10	329-4	1/4-20	7/16-14
		10	329-5	5/16-18	1/2-13
		10	329-6	3/8-16	9/16-12
		6	329-8	1/2-13	3/4-10
COARSE THREAD 1/2" to 1"	EZ-C816	6	329-8	1/2-13	3/4-10
		7	329-10	5/8-11	7/8-9
		7	329-12	3/4-10	1-8
		2	329-16	1-8	1-3/8-12
FINE THREAD #10 to 1/2"	EZ-F108	10	329-332	10-32	3/8-16
		10	329-428	1/4-28	7/16-14
		10	329-524	5/16-24	1/2-13
		10	329-624	3/8-24	9/16-12
		6	329-820	1/2-20	3/4-10
METRIC THREAD M6 to M12	EZ-M612	10	650-6	M6 -1.0	3/8-16
		10	650-8	M8 -1.25	1/2-13
		10	650-10	M10-1.5	9/16-12
		6	650-12	M12-1.75	3/4-10
METRIC INTERNAL/ METRIC EXTERNAL					
M3-0.5 to M8-1.25	EZ-M100	10	450-3	M3-0.5	M6-1.0
		10	450-4	M4-0.7	M8-1.25
		10	450-5	M5-0.8	M8-1.25
		10	450-6	M6-1.0	M10-1.5
		10	450-8	M8-1.25	M12-1.75
M8-1.25 to M16-2.0	EZ-M200	10	450-8	M8-1.25	M12-1.75
		10	450-10	M10-1.5	M16-2.0
		8	450-12	M12-1.75	M16-2.0
		5	450-16	M16-2.0	M24-3.0
303 STAINLESS STEEL, PASSIVATED					
COARSE THREAD 303 STAINLESS #10 to 1/2"	EZ-C303	10	303-3	10-24	3/8-16
		10	303-4	1/4-20	7/16-14
		10	303-5	5/16-18	1/2-13
		10	303-6	3/8-16	9/16-12
		6	303-8	1/2-13	3/4-10
FINE THREAD 303 STAINLESS #10 to 7/16"	EZ-F303	10	303-332	10-32	3/8-16
		10	303-428	1/4-28	7/16-14
		10	303-524	5/16-24	1/2-13
		10	303-624	3/8-24	9/16-12
		6	303-820	1/2-20	3/4-10



Refills available packed five or ten to a carton, depending on size.



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APPENDIX B

COMPUTER ANALYSIS RESULTS
FOR DIGITIZED INSPECTION

POLYNOMIAL REGRESSION..... T 20

POLYNOMIAL REGRESSION OF DEGREE 2

TABLE OF RESIDUALS

OBSERVATION NO.	Z VALUE,	X VALUE	Y VALUE	Y ESTIMATE	RESIDUAL
1	32.00000	62.50000	18.05701	18.06636	-0.00935
2	32.00000	66.50000	14.45200	14.42562	0.02638
3	32.00000	74.37500	8.46200	8.45704	0.00496
4	32.00000	82.25000	4.06400	4.07887	-0.01487
5	32.00000	90.12500	1.26400	1.29110	-0.02710
6	32.00000	98.00000	0.09600	0.09371	0.00229
7	32.00000	100.00000	0.02400	0.04286	-0.01886
8	32.00000	102.00000	0.11200	0.09460	0.01740
9	32.00000	109.87500	1.29500	1.29545	-0.00045
10	32.00000	117.75000	4.10400	4.08671	0.01729
11	32.00000	125.62500	8.48400	8.46837	0.01563
12	32.00000	133.50000	14.46000	14.44044	0.01956
13	32.00000	137.50000	18.04901	18.08293	-0.03392

THE FOCAL LENGTH IS 19.49683

THE FOCAL POINT IS LOCATED FOR Z = 32.000 AT X = 99.99138 AND Y = 19.53969

THE CORRELATION COEFFICIENT IS0.999963

POLYNOMIAL REGRESSION..... T 21

POLYNOMIAL REGRESSION OF DEGREE 2

TABLE OF RESIDUALS

OBSERVATION NO.	Z VALUE.	X VALUE	Y VALUE	Y ESTIMATE	RESIDUAL
1	36.00000	62.50000	18.10701	18.11714	-0.01013
2	36.00000	66.50000	14.49200	14.46446	0.02754
3	36.00000	74.37500	8.47600	8.47591	0.00008
4	36.00000	82.25000	4.06900	4.08256	-0.01356
5	36.00000	90.12500	1.26100	1.28439	-0.02339
6	36.00000	98.00000	0.09200	0.08140	0.01060
7	36.00000	100.00000	0.00100	0.02988	-0.02888
8	36.00000	101.99900	0.09900	0.08120	0.01780
9	36.00000	109.87500	1.29200	1.28370	0.00830
10	36.00000	117.75000	4.10000	4.08132	0.01868
11	36.00000	125.62500	8.47800	8.47411	0.00389
12	36.00000	133.50000	14.48500	14.46206	0.02294
13	36.00000	137.50000	18.08200	18.11449	-0.03249

THE FOCAL LENGTH IS 19.43846

THE FOCAL POINT IS LOCATED FOR Z = 36.000 AT X =100.00140 AND Y = 19.46835

THE CORRELATION COEFFICIENT IS1.000009

POLYNOMIAL REGRESSION..... T 22

POLYNOMIAL REGRESSION OF DEGREE 2

TABLE OF RESIDUALS

OBSERVATION NO.	Z VALUE.	X VALUE	Y VALUE	Y ESTIMATE	RESIDUAL
1	40.00000	62.50000	18.14401	18.15349	-0.00947
2	40.00000	66.50000	14.52000	14.49263	0.02737
3	40.00000	74.37500	8.48500	8.49053	-0.00553
4	40.00000	82.25000	4.07500	4.08690	-0.01190
5	40.00000	90.12500	1.26300	1.28178	-0.01878
6	40.00000	98.00000	0.08500	0.07513	0.00986
7	40.00000	100.00000	0.00700	0.02322	-0.01622
8	40.00000	101.99900	0.08300	0.07435	0.00864
9	40.00000	109.87500	1.28400	1.27818	0.00582
10	40.00000	117.75000	4.09600	4.08045	0.01555
11	40.00000	125.62500	8.48200	8.48118	0.00082
12	40.00000	133.50000	14.50400	14.48041	0.02359
13	40.00000	137.50000	18.11000	18.13982	-0.02982

THE FOCAL LENGTH IS 19.39824

THE FOCAL POINT IS LOCATED FOR Z = 40.000 AT X =100.00710 AND Y = 19.42146

THE CORRELATION COEFFICIENT IS1.000010

POLYNOMIAL REGRESSION.....   T 23

POLYNOMIAL REGRESSION OF DEGREE 2

TABLE OF RESIDUALS

OBSERVATION NO.	Z VALUE.	X VALUE	Y VALUE	Y ESTIMATE	RESIDUAL
1	44.00000	62.50000	18.16800	18.16830	-0.00031
2	44.00000	66.50000	14.53700	14.50460	0.03240
3	44.00000	74.37500	8.48500	8.49823	-0.01323
4	44.00000	82.25000	4.07500	4.09213	-0.01713
5	44.00000	90.12500	1.26400	1.28629	-0.02229
6	44.00000	98.00000	0.07400	0.08072	-0.00672
7	44.00000	100.00000	0.00200	0.02937	-0.02737
8	44.00000	102.00000	0.08200	0.08124	0.00076
9	44.00000	109.87500	1.28600	1.28879	-0.00279
10	44.00000	117.50000	4.09000	3.98286	0.10714
11	44.00000	125.62500	8.47800	8.50468	-0.02668
12	44.00000	133.50000	14.52200	14.51304	0.00896
13	44.00000	137.50000	18.14401	18.17776	-0.03375

THE FOCAL LENGTH IS 19.37660

THE FOCAL POINT IS LOCATED FOR Z = 44.000 AT X = 99.99512 AND Y = 19.40598

THE CORRELATION COEFFICIENT IS1.000010

POLYNOMIAL REGRESSION..... T 24

POLYNOMIAL REGRESSION OF DEGREE 2

TABLE OF RESIDUALS

OBSERVATION NO.	Z VALUE,	X VALUE	Y VALUE	Y ESTIMATE	RESIDUAL
1	48.00000	62.50000	18.18100	18.18907	-0.00807
2	48.00000	66.50000	14.54800	14.51894	0.02906
3	48.00000	74.37500	8.48600	8.50174	-0.01574
4	48.00000	82.25000	4.07600	4.08719	-0.01119
5	48.00000	90.12500	1.26500	1.27531	-0.01031
6	48.00000	98.00000	0.07700	0.06606	0.01093
7	48.00000	100.00000	0.00000	0.01416	-0.01416
8	48.00000	102.00000	0.07800	0.06561	0.01238
9	48.00000	109.87500	1.28300	1.27308	0.00992
10	48.00000	117.75000	4.08700	4.08321	0.00379
11	48.00000	125.62500	8.48100	8.49598	-0.01498
12	48.00000	133.50000	14.53400	14.51141	0.02259
13	48.00000	137.50000	18.16501	18.18063	-0.01562

THE FOCAL LENGTH IS 19.34778

THE FOCAL POINT IS LOCATED FOR Z = 48.000 AT X =100.00430 AND Y = 19.36194

THE CORRELATION COEFFICIENT IS0.999965

POLYNOMIAL REGRESSION..... T 25

POLYNOMIAL REGRESSION OF DEGREE 2

TABLE OF RESIDUALS

OBSERVATION NO.	Z VALUE,	X VALUE	Y VALUE	Y ESTIMATE	RESIDUAL
1	52.00000	62.50000	18.18100	18.18979	-0.00878
2	52.00000	66.50000	14.54800	14.51939	0.02861
3	52.00000	74.37500	8.48600	8.50190	-0.01590
4	52.00000	82.25000	4.07600	4.08733	-0.01133
5	52.00000	90.12500	1.26800	1.27570	-0.00769
6	52.00000	98.00000	0.07700	0.06700	0.01000
7	52.00000	100.00000	0.00500	0.01527	-0.01027
8	52.00000	102.00000	0.07900	0.06694	0.01206
9	52.00000	109.87500	1.28500	1.27537	0.00963
10	52.00000	117.75000	4.08700	4.08673	0.00027
11	52.00000	125.62500	8.48300	8.50103	-0.01803
12	52.00000	133.50000	14.54100	14.51828	0.02272
13	52.00000	137.50000	18.17601	18.18852	-0.01251

THE FOCAL LENGTH IS 19.34439

THE FOCAL POINT IS LOCATED FOR Z = 52.000 AT X =100.00070 AND Y = 19.35966

THE CORRELATION COEFFICIENT IS0.999966

POLYNOMIAL REGRESSION..... T 26

POLYNOMIAL REGRESSION OF DEGREE 2

TABLE OF RESIDUALS

OBSERVATION NO.	Z VALUE,	X VALUE	Y VALUE	Y ESTIMATE	RESIDUAL
1	56.00000	62.50000	18.16800	18.17725	-0.00924
2	56.00000	66.50000	14.53700	14.51020	0.02680
3	56.00000	74.37500	8.48500	8.49816	-0.01316
4	56.00000	82.25000	4.07500	4.08763	-0.01263
5	56.00000	90.12500	1.27600	1.27859	-0.00259
6	56.00000	98.00000	0.07600	0.07105	0.00494
7	56.00000	100.00000	0.00500	0.01939	-0.01439
8	56.00000	102.00000	0.08900	0.07103	0.01796
9	56.00000	109.87500	1.28800	1.27846	0.00954
10	56.00000	117.75000	4.08700	4.08738	-0.00038
11	56.00000	125.62500	8.47900	8.49780	-0.01880
12	56.00000	133.50000	14.52900	14.50971	0.01929
13	56.00000	137.50000	18.16800	18.17673	-0.00872

THE FOCAL LENGTH IS 19.36176

THE FOCAL POINT IS LOCATED FOR Z = 56.000 AT X =100.00030 AND Y = 19.38115

THE CORRELATION COEFFICIENT IS0.999966

POLYNOMIAL REGRESSION..... T 27

POLYNOMIAL REGRESSION OF DEGREE 2

TABLE OF RESIDUALS

OBSERVATION NO.	Z VALUE.	X VALUE	Y VALUE	Y ESTIMATE	RESIDUAL
1	60.00000	62.50000	18.14401	18.15697	-0.01295
2	60.00000	66.50000	14.52000	14.49427	0.02573
3	60.00000	74.37500	8.48500	8.48940	-0.00440
4	60.00000	82.25000	4.07500	4.08413	-0.00913
5	60.00000	90.12500	1.28000	1.27847	0.00154
6	60.00000	98.00000	0.06400	0.07240	-0.00840
7	60.00000	100.00000	0.00000	0.02081	-0.02081
8	60.00000	102.00000	0.09100	0.07241	0.01859
9	60.00000	109.87500	1.29200	1.27845	0.01355
10	60.00000	117.75000	4.08500	4.08410	0.00089
11	60.00000	125.62500	8.48100	8.48936	-0.00835
12	60.00000	133.50000	14.51000	14.49421	0.01579
13	60.00000	137.50000	18.14601	18.15691	-0.01089

THE FOCAL LENGTH IS 19.38467

THE FOCAL POINT IS LOCATED FOR Z = 60.000 AT X =100.00000 AND Y = 19.40550

THE CORRELATION COEFFICIENT IS0.999965

POLYNOMIAL REGRESSION..... T 28

POLYNOMIAL REGRESSION OF DEGREE 2

TABLE OF RESIDUALS

OBSERVATION NO.	Z VALUE,	X VALUE	Y VALUE	Y ESTIMATE	RESIDUAL
1	64.00000	62.50000	18.10701	18.12215	-0.01514
2	64.00000	66.50000	14.49200	14.46769	0.02431
3	64.00000	74.37500	8.47600	8.47639	-0.00039
4	64.00000	82.25000	4.06900	4.08120	-0.01220
5	64.00000	90.12500	1.29200	1.28213	0.00987
6	64.00000	98.00000	0.06700	0.07917	-0.01217
7	64.00000	100.00000	0.01300	0.02783	-0.01483
8	64.00000	102.00000	0.09200	0.07941	0.01258
9	64.00000	109.87500	1.29100	1.28331	0.00769
10	64.00000	117.75000	4.08500	4.08331	0.00169
11	64.00000	125.62500	8.47200	8.47944	-0.00743
12	64.00000	133.50000	14.48800	14.47168	0.01632
13	64.00000	137.50000	18.11601	18.12662	-0.01060

THE FOCAL LENGTH IS 19.42703

THE FOCAL POINT IS LOCATED FOR Z = 64.000 AT X = 99.99768 AND Y = 19.45486

THE CORRELATION COEFFICIENT IS0.999968

POLYNOMIAL REGRESSION..... T 29

POLYNOMIAL REGRESSION OF DEGREE 2

TABLE OF RESIDUALS

OBSERVATION NO.	Z VALUE.	X VALUE	Y VALUE	Y ESTIMATE	RESIDUAL
1	68.00000	62.50000	18.05701	18.07626	-0.01926
2	68.00000	66.50000	14.45200	14.43153	0.02047
3	68.00000	74.37500	8.46200	8.45655	0.00545
4	68.00000	82.25000	4.06400	4.07390	-0.00989
5	68.00000	90.12500	1.30100	1.28360	0.01740
6	68.00000	98.00000	0.08400	0.08563	-0.00163
7	68.00000	100.00000	0.00800	0.03494	-0.02694
8	68.00000	102.00000	0.09300	0.08696	0.00604
9	68.00000	109.87500	1.29500	1.29014	0.00486
10	68.00000	117.75000	4.08900	4.08568	0.00332
11	68.00000	125.62500	8.47100	8.47354	-0.00254
12	68.00000	133.50000	14.47000	14.45376	0.01624
13	68.00000	137.49900	18.08701	18.10019	-0.01318

THE FOCAL LENGTH IS 19.47308

THE FOCAL POINT IS LOCATED FOR Z = 68.000 AT X = 99.98708 AND Y= 19.50803

THE CORRELATION COEFFICIENT IS1.000026

POLYNOMIAL REGRESSION.....AVERAGE

POLYNOMIAL REGRESSION OF DEGREE 2

TABLE OF RESIDUALS

OBSERVATION NO.	Z VALUE,	X VALUE	Y VALUE	Y ESTIMATE	RESIDUAL
1	50.00000	62.50000	18.13101	18.14200	-0.01099
2	50.00000	66.50000	14.51000	14.48309	0.02691
3	50.00000	74.37500	8.47900	8.48444	-0.00544
4	50.00000	82.25000	4.07200	4.08376	-0.01176
5	50.00000	90.12500	1.27300	1.28103	-0.00802
6	50.00000	98.00000	0.07900	0.07628	0.00271
7	50.00000	100.00000	0.00600	0.02478	-0.01878
8	50.00000	102.00000	0.09000	0.07632	0.01367
9	50.00000	109.87500	1.28900	1.28122	0.00778
10	50.00000	117.75000	4.09100	4.08408	0.00692
11	50.00000	125.62500	8.47900	8.48491	-0.00591
12	50.00000	133.50000	14.50400	14.48371	0.02029
13	50.00000	137.50000	18.12401	18.14270	-0.01869

THE FOCAL LENGTH IS 19.40451

THE FOCAL POINT IS LOCATED FOR Z = 50.000 AT X = 99.99963 AND Y = 19.42929

THE CORRELATION COEFFICIENT IS0.999963

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