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ABSTRACT

The reflecting concentrator of a parabolic trough solar collector system comprises approximately 40% of initial system cost. The parabolic concentrator structure is also the most influential component in determining overall system efficiency. As such, the reflector structure must be inexpensive, accurate and dimensionally stable for long periods of time. One material-design system with the potential to satisfy those requirements is a rib-stiffened design formed from sheet molding compound. An advantage of such a structure is that a silvered glass reflective surface could be molded into the support structure during the forming operation. To examine the feasibility of such a molded structure, parabolic test moldings have been fabricated from a general purpose sheet molding compound with flat chemically strengthened glass, flat annealed glass, and thermally formed glass. The test panel configuration was a 1.22 m x 0.61 m, 45° rim angle (0.762 m focal length) parabola. Attempts to mold with annealed sheet glass (1 mm thick) and thermally formed glass (1.25 mm thick) were unsuccessful; only the chemically strengthened glass (1.25 mm thick) was strong enough to survive molding pressures. Because of the mismatch in thermal expansion between glass and sheet molding compound, the as-molded panels contained a sizeable residual stress. This paper gives the results of dimensional changes taking place in the panels under accelerated thermal cycling and outdoor aging conditions; these results are compared to an analytical model of the laminate. In addition, the sheet molding compound has been examined for thermomechanical properties and flow behavior in the rib sections. Results indicated that lowering the thermal expansion coefficient of the sheet molding compound through material modifications would produce a more stable structure.

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CONTENTS

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INTRODUCTION

The advent of more expensive energy than this nation has been accustomed to in the past has stimulated substantial efforts toward the development of solar energy as a potential alternative to more conventional energy sources. Sandia National Laboratories (Albuquerque), as a prime contractor to the Department of Energy, has been engaged with industry in the development of solar technology for several years [1-3]. Primary emphasis in the solar thermal area has been in parabolic trough line-focusing collectors with output fluid temperatures of 200 - 600^{O}F. Approximately one-half of U. S. industrial process heat usage is below 600^{O}F; therefore, solar thermal systems which are efficient in that temperature range are of interest.

A parabolic trough collector (Fig. 1) must track the sun along one axis so as to maintain the sun in its focal plane. The incoming rays of light are nearly parallel and are reflected and concentrated at the focus of the parabola where the receiver tube is placed (Fig. 2).

The principle structural member of a focusing collector system is the reflector support structure. It must provide the correct optical shape for the reflective surface which it supports, and maintain that shape within specified tolerances during operation under the influences of wind, gravity and thermal effects. The reflector support structure must also survive and protect the reflective surface under extreme weather conditions, and withstand the detrimental effects of long-term exposure to the environment.

This paper will discuss an approach to the fabrication of a line-focusing parabolic trough reflector structure which offers the potential of high performance while utilizing mass production type technology with potential for low cost. The concept is one of a molded structure of fiber reinforced plastic with an integrally molded silvered glass reflective surface. Sheet molding compound (SMC), a mixture of glass fibers and inorganic fillers in polyester resin, has been selected for evaluation as representative of reinforced plastic molding materials.

The purpose of the work described in this paper was to establish the feasibility of molding glass mirrors into SMC structural trough panels. If the effort proved successful, the next stage of development would be demonstration of the structure in a trough collector (Fig. 3) which incorporates individual SMC reflector panels (Fig. 4). The trough has a 2 x 6 m aperture with six individual SMC panels mounted on a torque tube as the main support structure.

Glass Reflectors

Second surface silvered glass mirrors are considered to be the leading contender in the field of reflector materials for the following reasons: (1) there is an established technology and production facilities for silvered mirrors; (2) the smoothness of the glass surface gives high specularity; (3) glass has good durability in a weathering environment including UV and abrasion resistance; (4) glass has a lower propensity to dirt accumulation and easier cleaning than plastic films; and, (5) raw materials for glass are plentiful. The major design considerations of glass mirrors are weight and fragility. Specular reflectances of .88 to .95 can be achieved with glass reflectors.

The primary glass materials for reflector mirrors are chemically strengthened glass and thermally formed (sagged) glass. The chemically strengthened glasses are usually aluminosilicates or borosilicates processed in an ion exchange bath to achieve ultimate tensile strengths of 40 - 50,000 psi. A piece of this strengthened glass is very similar to a piece of medium strength aluminum alloy. The Young's Modulus is the same, 10×10^6 psi; the two pieces are literally of the same flexibility except that when the alunimum yields, the glass fractures and dices.

The sagged glass panels are usually low iron float glass of thicknesses of .060 - .090 inch formed by heating and then pressing or allowing to gravity sag to the mold contour. Curved panels are more difficult to silver.

Reflector Contour Accuracy

Collector reflector performance is also dependent on the accuracy of the parabolic contour. By definition for a parabola, incoming parallel light rays are reflected so that they all converge at the focus of the parabola. Inaccuracies in the parabolic contour would cause the reflected light to miss the focus.

A theoretical parabolic surface can be defined easily. A tolerance zone on either side of the true parabola can be specified, sometimes with a very liberal tolerance; however, the critical factor is the statistical summary of the slope errors* of the entire reflector [4, 5]. A 2.5 milliradian rms standard deviation slope error (17 mrad = 1°) is required for a high performance reflector structure.

Since a reflector structure is an optical device, optical means were developed to inspect it. A laser ray trace device was designed and developed which can scan the parabola with multiple transverse traces from rim to rim [6-9]. The position of the reflected beam of light is sensed at or near the focus by a detector and the error recorded. The rms slope error is determined from a large number of discrete points on the mirror surface. Laser ray trace data can also be utilized to provide other valuable information regarding the characteristics of the reflector such as focal length, warping, local areas of deformation, etc. The laser ray trace is not a production inspection tool; it is a valuable R & D and process development tool.

EARLY INVESTIGATION OF SMC

Sheet molding compound has been used for 15-20 years in the manufacture of business machine cases, electrical components, and construction materials. More recently, the need to produce

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*Slope error is defined as the deviation from the theoretical slope of a particular point on a parabolic surface.

lighter weight, more efficient automobiles has led to the replacement of sheet metal assemblies with molded SMC by all the major automobile manufacturers. The primary purposes are reduction of weight and fabrication of a single molded part to replace a complex assembly.

In addition to being a material/design presently used in mass production, other factors indicated that SMC was potentially attractive for use in solar reflector structures. Those considerations include cost, tailorable thermal and mechanical properties, durability in outdoor weathering [10], and a proven technology for the fabrication of large curved structures [11, 12].

To further investigate the potential for SMC as a reflector structure material, panels of SMC were included in a project aimed at investigating a wide variety of materials, materials combinations, and fabrication techniques suitable for producing parabolic trough structures. Parabolic panels 4 x 2 ft, with a 45° rim angle, and 30 inch focal length were fabricated on an aluminum male mold. Haveg Industries, Santa Fe Springs, California, produced the female part of the mold with the rib pattern shown in Fig. 5, and molded a number of units with a general purpose SMC. Various reflector materials were applied, the units were inspected with the laser ray trace, and then subjected to an accelerated thermal cycling environmental testing program.

The thermal cycling consisted of an eight-hour cycle with two hours at each extreme temperature of $-20^{o}F$ and $+130^{o}F$, and a two-hour transition time between the extremes. Relative humidity was controlled between 45% and 85%. Laser inspection was conducted at regular intervals. The SMC parts proved to be dimensionally stable; little change was observed in focal length or rms slope error after 13 months of chamber exposure [13].

SMC trough panels potentially offer two additional significant advantages over other fabrication techniques: 1) molding of the glass reflector into the SMC structure, thus eliminating secondary bonding operations; and 2) providing bonded, total encapsulation protection for the silvered coating on the glass which enhances a long-term environmental capability.

Several attempts at molding glass mirrors into SMC were made by Haveg for Sandia and other companies. There were some successes and some failures. Flat molded sections tended to survive. Molding with annealed glass mirrors which were elastically pressed to a curved section generally fractured. Bare glass would not adhere to the SMC. The SMC generally bonded to the paint of the silver/copper/paint coating.

This early work with SMC established it as a potential material for parabolic trough reflector structures; it also delineated specific problem areas which required further investigation.

MOLDING STUDIES

The primary objective of the molding program was to determine the survivability of chemically strengthened and sagged glass in the SMC molding operation. Secondary objectives included the determination of: (1) the effects of molding temperatures and pressures on glass and silver coatings; (2) "sink" effects at ribs; (3) the effect of the bimaterial response of two materials with different coefficients of thermal expansion on the optical accuracy of a SMC/glass part; (4) the effect of glass on one face of the part on the cure of the SMC; (5) the environmental durability of panels with molded-in glass mirrors; and (6) the appropriate processing parameters and handling and preheating of the glass.

Part Description

Structural analysis indicated that SMC panels could be simplified and lightened by the elimination of some internal ribs and still meet design requirements [14]. To evaluate the simplified concept, the previously used 4 x 2 ft mold was modified to allow fabrication of panels in two configurations. Configuration I consisted of a curved 4 x 2 ft front face with a peripheral rib or flange on the back side all the way around the part; there were also centerline ribs running in both directions. All ribs were 1.875-in deep, .250-in thick at the root and .125-in thick at the tip. Configuration II (2-rib) deleted the centerline ribs. The SMC face of the panel was 0.155-in thick.

A total of 18 parts were to be molded in the two configurations. For each configuration, it was planned to mold three units of all-SMC (no glass), three units with the Code 0317 chemically strengthened glass mirrors, and three units with annealed Code 0317 glass that had been thermally formed (sagged) to the parabolic contour. The SMC material selected was Haveg's 9220-30, a low profile, $CaCO_3$ filled formulation with 30 weight percent 1-in long chopped fiberglass reinforcement.

Molding Procedures

After minor adjustments of the charge pattern and weight, the three all-SMC parts were molded successfully. The female mold half was attached to the top (fixed) part of the press and the male (parabolic face) half of the mold to the lower (moveable) part of the press. Their alignment was such that the molded SMC face between the two mold halves was not of uniform thickness. The thickness varied between .090 to .160-in. To alleviate this variation, mechanical stops in the form of thin metal shims were placed on the flat faces between the two mold halves; these shims provided parallel alignment of the two halves and produced SMC parts with uniform face thicknesses. This use of stops may have been to the detriment of the material characteristics of the molded SMC due to the lack of full and constant pressure on the SMC during its cure cycle.

The charge for configuration I (internal ribs) consisted of a stack of sheets of SMC over 90% of the mold aperture plus two or three strips of SMC about 1-3/4" wide running along the two centerlines to provide material for those ribs. The as-molded appearance of a configuration I part is shown in Fig. 6.

The molding of the chemically strengthened glass was attempted with the same SMC charge. The flat glass mirror was preheated to 280°F to avoid thermal shock on the glass when placed in the mold. Two different approaches were taken in loading the chemically strengthened glass and SMC charge. In one approach, the heated mold was opened, the preheated glass was placed in the mold and the charge was placed on top of the silvered side of the glass. The weight of the charge on the flat glass caused it to flex downward and almost conform to the male mold. The position of the glass was checked and the mold closed. Mold parameters were 670 psi and 300°F. The other sequence was to remove the preheated glass from the oven, place the SMC charge on the silvered side of the glass and lower this combination into the mold, position it carefully and close the mold.

Considerable care was taken to assure that the face of the male mold was clean. Any particle of grit between the glass and the mold would be highly likely to cause fracture of the glass. The first unit of stressed glass molded quite successfully. The second one was heard to fracture just as the mold completed closing. The part was cured and removed from the mold. Fracture of a stressed piece of glass can be traced to its origin easily by the dicing pattern in the glass. The source pieces of glass were post-mortemed; it was determined that a small piece of aluminum grit had been present under the glass and caused failure. The next eight pieces of strengthened glass were molded successfully with no problems.

It should be noted that the pressure of the SMC charge on the glass during the molding process forced the glass against the mold and did not allow either the resin or fiberglass of the SMC to run under the glass. The front surface of the glass was clean except for some mold release which required cleaning with a solvent. A molded part with a chemically strengthened glass mirror surface is shown in Fig. 7.

Molding of the sagged glass panels was only slightly different in process. The sagged and annealed curved glass panels were too weak to justify placement of the SMC charge on the glass prior to placement in the mold; therefore, the glass was placed in the mold and allowed to be heated by the mold for a few minutes prior to placement of the charge on the back of the glass.

The molding of the sagged glass units resulted in breakage in the glass in all four units attempted. The charge pattern in the last unit was increased to the maximum practical. The resultant fracture pattern was slightly different than the other three units but no major conclusions can be drawn from this difference. It appears that the strength of the chemically strengthened glass is important to surviving SMC molding conditions.

It appears that the accuracy of the sagged glass does not equal that of the male mold; therefore, when the pressures of molding force the glass to conform to the mold contour, the glass strenth is not sufficient to survive the developed stresses. There is also a temperature difference developed across the thickness of the glass. The mold (bottom) side of the glass is at 300°F; the upper side of the glass (the silvered side) is cooled by the SMC charge which is initially at room temperature. The temperature differential induces tension in the silvered side of the glass. The combined stresses appear to be higher than glass can stand, and it fractures. The prospects of molding sagged panels are not promising.

EVALUATION OF MOLDED UNITS

Evaluation of the molded SMC parabolas was conducted in four areas: (1) surface mapping with the laser ray trace; (2) mechanical property measurements as a function of location in the structure; (3) thermochemical analysis (degree of cure, component volume fractions, filament orientation, etc.); and, (4) dimensional stability under temperature and humidity cycling conditions.

As-Molded Optical Characteristics

Laser ray trace results for the SMC panels in the as-molded condition are given in Table I. Comparison of the 2-rib and 3-rib results for the all-SMC units (no molded in glass) shows that both rib configurations are within one percent of the mold focal length. Configuration I (3-rib) has closed slightly (lower focal length) with respect to the mold and to Configuration II. A similar result was seen on previous moldings with internal ribs [6, 13]. The cause of the high slope errors in Configuration I is unknown. Examination of plots of slope error vs. surface location for Configuration I shows a general surface roughness between the ribs and a spike in slope error along the vertex. Visual examination of the 3-rib panels revealed a noticeable sink or depression along the vertex rib. Sink was not evident at the rim-to-rim internal rib.

Slope errors in Configuration II (2-rib panels) are uniform over the surface except for a small increase at the vertex and are comparable to previously observed results [6, 13]. The distortion at the vertex may be due to the mold itself because similar behavior has been seen in other materials. It appears that the rib spacing in the 3-rib design is short enough to influence the cure shrink behavior in the face sheet which causes deviations from the mold surface.

Optical characteristics for 2- and 3-rib panels with molded-in silvered glass surfaces in the as-molded condition are also shown in Table I. Both configurations appear equivalent in behavior with a molded-in, thermally-formed (sagged) glass surface. In both cases, the differential expansion between the glass and SMC has caused the parabola to open up to a longer focal length. The increase in focal length from the mold represents a change of 4.5 percent. Slope errors with the sagged glass surfaces are on the order expected for glass surfaces, i.e., 1.5-2.0 mrad. The surface plots of slope error show them to be quite smooth and uniform except for some distortion at the vertex. Little difference can be seen between the 2- and 3-rib designs, even at the vertex. There is no evidence of sink effects or of an effect of the cracks on the laser measurements.

As shown in Table I, slight differences in optical characteristics are seen between the two designs with molded-in chemically strengthened glass surfaces. The 3-rib panels have opened slightly more than the 2-rib. Such an effect might be expected because the higher section modulus of the 3-rib panel would allow the SMC to influence the final geometry to a greater extent. That a similar difference was not seen with the thermally formed glass surfaces may be due to the cracks in the glass allowing some amount of stress relief. Higher slope errors are also evident in the strengthened glass surface units. Examination of the slope error plots and visual observation of the strengthened glass panels revealed that the glass did not form into a smooth parabolic arc, but rather deformed in a series of short straight sections or chords to the arc. Such behavior results in sunlight being reflected in a series of bundles as seen in Figure 7, rather than in an ideal uniform arc. Chording was also observed in the 2-rib panels, but to a lesser extent. How the SMC flow and cure behavior during molding influences the glass deformation mode is unknown and will require further study.

The last two panels molded in Configuration II utilized Haveg's 9230-30 formulation and chemically strengthened glass in order to provide parts of a different SMC material. The increase in focal length was slightly greater than for the 9220-30 material; similarly the slope error was greater (See Table I). The increase in focal length is indicative of the higher expansion of 9230-30. Both of the 9230-30 units resulted in damage to local areas of the silver/glass interface during molding. For unknown reasons the SMC material pulled the silver loose from the glass in areas along one side of one unit and both sides of the other. Possible causes include: a higher viscosity of the material during molding; possible effects of a different resin, or poor quality silvering.

Mechanical Properties

Tensile specimens were machined from an SMC panel and a panel with a sagged glass surface (both Configuration I) to determine whether the glass affected SMC flow or cure during molding. Specimens were taken at various locations in the ribs and face of the parts. Six specimens of each type were tested on an Instron universal test machine at a cross head speed of 0.05 in/min. Strains were monitored with a strain gage extensometer.

Modulus and strength results are given in Table II. The extreme scatter evident in the data makes it difficult in some cases to draw meaningful conclusions about the flow behavior of the SMC. Some of the variation in the mechanical properties may be due to a lack of pressure throughout cure because stops were used between the mold halves. Scatter is also a characteristic of the variability of SMC itself. Coefficients of variation of 15 percent in modulus and 20 percent in strength are routinely seen for SMC tensile tests [15].

Some amount of anisotropy is seen between the face material and rib material in the SMC units as evidenced by the higher modulus in the ribs (Table II). Little difference is seen between the rib depth and length which indicates that no preferred orientation is taking place during flow into the ribs. Also shown in Table II are results from flat panels which were pressed to stops. The low values from the flat sheets are indicative of the need to provide adequate pressure on the SMC during cure.

Comparison of the rib properties with and without a glass surface (Table II) indicates that the glass imparts little or no influence on the flow behavior of the SMC. The low strengths seen in the rib depth specimens with sagged glass are believed due to a lack of uniformity in thickness and are not representative of the material itself.

Good adhesion between the SMC and the glass/Ag/Cu/paint mirror laminate is critical to the mechanical and environmental performance of the SMC reflectors. A shear test was devised to evaluate the quality of the SMC-mirror bond. Thick adherend adhesive testing technology as discussed in Ref. 16 was used to minimize bending on the specimen. The shear specimens were taken from flat panels molded with mirrored float glass surfaces because a valid shear test could not be devised for curved specimens. Failure in these specimens initiated at flaws in the float glass so the determined shear strength of 2200 psi must be viewed as a lower bound. Once initiated, the crack always propagated within the paint layer.

Note the effect of the 9230-30 material on the silver/glass interface discussed earlier. There is concern regarding the entire glass/silver/copper/paint/SMC interface area.

Thermochemical Characterization

There was some concern about the cure behavior of the SMC near the glass surface because of the poor heat transfer through the glass. To determine degree of cure, through-the-thickness thermal expansion curves were determined for the SMC faces with and without glass. Expansion was measured on a Perkin-Elmer Thermomechanical Analyzer TMS 1. A 5 gram load was applied to the 0.15 inch diameter expansion probe. Three specimens each of SMC with and without a glass surface were run. Averaged results for the two types of specimens are plotted in Fig. 8. A somewhat higher expansion is seen in the SMC with a glass surface. Higher expansion in thermoset resins is indicative of a lower cross-link density or degree of cure. The effect on glass transition temperature, T_g, is slight, however. T_g is determined from the curves in Fig. 8 as the intersection of tangents drawn to the linear sections of the curves above and below the inflection point or knee. Using that method, the T_g of the SMC with glass is lowered 11°F to 289°F compared to the 300°F T_g of the all-SMC panels. Such a slight effect is not considered significant to the performance of a reflector structure; however, it should be noted that these development units were subjected to a long cure cycle (15 min). Use of a short, production cure cycle may exaggerate the lower degree of cure of the SMC near the glass.

Chemical analysis was also performed on the molded panels with and without glass. The objective of these evaluations was to determine whether any flow separation of components occurred in the two types of units. Weight and volume fractions of resin, glass, and $CaCO_3$ from the face and rib sections are given in Table III. Resin content, which includes low profile additives and other organics besides the polyester resin, was determined by burnoff. $CaCO_3$ content was determined by dissolution in 4 percent HCl. Glass content was determined by weighing the residue after burnout and dissolution. Voids were determined by difference. Filament orientation could be seen if the burnout and dissolution steps were conducted carefully. No preferred filament orientation was evident in any of the samples. Three separate samples were run in each location to obtain the data given in Table III. The volume fraction data in Table III shows no apparent effect of the glass on flow of the SMC. The only trends which are discernible are an increase in the variability of the constituents in the rib sections and a higher void content in the ribs of both all-SMC and glass surface panels.

Thermocycling Behavior

As discussed previously, the glass-SMC thermal expansion mismatch results in a bi-material effect in the panel during cooldown from molding temperature. The SMC attempts to contract more than the glass producing residual stresses in both materials as the panel opens up to a longer focal length. The resultant stresses are compression in the glass, tension in the SMC face, shear at the interface and compression near the tip of the ribs. The SMC material will in time tend toward stress relief; the molded SMC may creep, particularly at elevated temperatures. Such stress relief behavior results in changes in the focal length of the molded panel. Significant changes in a part in service would be unacceptable due to decreased performance of the collector.

To examine the dimensional stability of the molded panels under accelerated conditions, some of the molded panels were thermocycled in the previously used environmental chamber. The panels were removed on a periodic basis and mapped with the laser ray trace. A plot of focal length vs. number of cycles for the Configuration I panels is given in Figure 9. Since only one specimen of a given type was subjected to the thermocycling environment, a 95 percent confidence level for the laser technique is shown for each data point. The results in Figure 9 show that focal length initially changes with time. Focal length of the glass surface parabolas decreases until a stable value is reached after approximately 50 cycles. Continued cycling has little immediate effect. After 291 cycles, focal length has been reduced only 0.3 percent. The all-SMC parabola displayed the opposite behavior by initially increasing in focal length (Fig. 9). Again, stability was attained after approximately 50 cycles. Focal length changes in the all-SMC panel are believed to be due to the relief of molding stresses caused by shrinkage.

Surface slope errors in the Configuration I panels were also affected by thermocycling. The 2.5 mrad nominal slope error seen in parabolas with a strengthened glass surface (Table I) was reduced to 1.8 mrad after 25 cycles. Additional cycling produced no further change in slope error up to 291 cycles. Chording of the strengthened glass surface was noted to decrease and virtually disappear visually after 25 cycles. The sagged glass surface panel also stabilized at a slope error of 1.8 mrad after 25 cycles.

Slope errors in the all-SMC panel were also reduced by thermocycling, but at a much slower rate. The initial 3.36 mrad slope error (Table I) dropped to 2.70 mrad after 25 cycles, to 2.42 mrad after 150 cycles, and finally to 2.08 mrad after 420 cycles.

No firm conclusions as to the long term environmental durability of the SMC/glass reflectors can be drawn from the data in Fig. 9 because of the short duration of the test. It does appear, however, that the units may be dimensionally stable after an initial stress relief or annealing cycle. In addition, the quality of the SMC-paint bond appears to be good. No deterioration of the silver has been observed in the chemically strenthened glass panels. Only very limited silver deterioration has been observed along the cracks in the sagged glass after 420 cycles.

Cycling results for the Configuration II panels are given in Fig. 10. A similar response is seen with a strengthened glass surface compared to the Configuration I panel. A smaller overall change in focal length is shown by the Configuration II panel which is indicative of the lower stiffness of the SMC structure. After the initial annealing stage, both configurations stabilized at a 31.0 inch focal length which then dropped to 30.9 inches after 291 cycles. The all-SMC Configuration II panel displayed little change in focal length with thermocycling (Fig. 10). The strong influence of the center rib (Configuration I) on the cure behavior of the SMC may be seen by comparing the all-SMC units in Figs. 9 and 10.

Thermocycling results for the panel molded with the higher expansion 9230-30 material and a strengthened glass surface are also shown in Fig. 10. After initially appearing to follow the annealing trend displayed by the units with the 9220-30 material, the 9230-30 SMC panel showed an unexpected drop in focal length above 200 cycles. The reasons for this behavior are unknown at the present time.

The slope errors of those units which had molded-in-glass reflectors (strengthened or annealed) decreased during thermocycling. Original values (Table I) decreased and tended to stabilize at about 2.0 mrad. The all-SMC 3-rib unit also stabilized at about 2.0 mrad. The all-SMC units which were thermocycled showed a slight decrease in slope error (2.17 to 1.7 mrad). The reasons for these changes can be conjectured. All parts fabricated on this male mold have demonstrated a chording effect which is believed to be a replication of the mold. The molding of the SMC units forced the glass to conform to the actual contour of the mold during curing. As the SMC material was stress relieved (or annealed) during thermocycling, the structural stiffness of the glass, with its significantly higher Young's modulus, reasserted itself and dominated the laminate contour. The glass assumed a more uniform arc as the SMC responded to the thermocycling by creeping or stress relieving.

Stress relief may be the better term to describe the phenomenon which produces a decrease in the focal length, since creep does not typically occur at the low stress levels indicated by the analytical model. A greater understanding of the time/temperature/stress relief mechanism is needed. Similarly, an annealing schedule is needed which would stress relieve the part and take it to a stable state prior to installation in the field. Consistency in the SMC material characteristics would be of major importance.

Analysis of Bi-material Effects

An analytical model of the SMC/glass structure was developed based on laminate theory to predict the panel's response to the differential expansion between the glass and the SMC. Calculations with the model assumed the glass and the SMC achieved a common temperature (300°F) in the mold during cure. As cooling began upon extraction from the mold, the SMC hardened at a temperature of 260°F where the bi-material phenomenon began to take place. As the panel cooled to room temperature (assumed 60°F), the SMC would attempt to shrink more than the glass, causing the panel to open up.

The theory indicated that the Young's modulus of the SMC had a minor effect. Calculations with all other variables held constant while varying E for the SMC indicated that E of 1.0 to 1.5 x 10^6 psi made only a slight difference in the resultant focal length or the stresses in the laminate. The main driver in the laminate reponse is the expansion coefficient (α) of the SMC. Slight variations in the expansion (from 10 to 11 x 10^{-6}/°F) make notable differences in the focal length and the resultant stresses in the laminate. Obviously, variations of the expansion coefficient within a molded part, would cause inconsistent, unpredictable responses.

In attempting to correlate the observed laser ray trace data and theoretical focal length changes, calculations were made based on the following conditions:

Glass $E = 10 \times 10^6$ psi; $\alpha = 5 \times 10^{-6}$ in/in°F
SMC $E = 1.2 \times 10^6$ psi; $\alpha = 10.5 \times 10^{-6}$ in/in°F
$T = 200$°F

Mold focal length was 30.00 inches

Results for a Configuration I unit with strengthened glass predicted a focal length change from 30.00 to 31.766. Actual laser inspection data showed an average focal length of 31.79 (Table I). Configuration I units with sagged glass and Configuration II units with sagged and chemically strengthened glass all defied theory and produced actual focal lengths of about 31.35 inches (Table I). Predicted focal length for Configuration II units with the same thermal expansion and Young's Modulus was 32.015 inches. A decrease in thermal expansion from 10.5 to 8.8 x $10^{-6}/^{o}F$ would explain the lower resultant focal length. Additional work on correlation is needed.

The changes in focal length experienced during thermal cycling of glass units were not expected. No predictions were made regarding these changes.

FUTURE

The next step in development of SMC trough panels with molded in glass reflectors is that of design and fabrication of full size panels which can be assembled into a functional trough collector. This design has been completed. From proposals received on a competitive procurement, selection was made and a contract placed with the Budd Company, Technical Center, Ft. Washington, Pa., to design and fabricate tooling and to produce a quantity of SMC/glass panels for evaluation.

The basic design concept of a 2 x 6 m trough was shown in Fig. 3. The individual panels, which mount on the longitudinal torque tube, are shown in Fig. 4. The present panel design extends only from vertex to rim (1 meter) and one meter in length; two of these panels are fastened together along the vertex to form the full 2 m rim to rim trough section. The half parabola was chosen primarily on the basis of lower tooling costs for development. A one-piece rim-to-rim panel would be used for production units.

The tooling has been designed and fabricated. Parts are to be molded in June, 1980. The parts will be inspected to determine their accuracy and evaluated. The objectives of this project are to establish that SMC mass production techniques can achieve the desired tolerances and performance and will have the required long-term environmental capability.

SUMMARY

Reflector structures for parabolic trough collectors fabricated of SMC with molded-in-glass mirrors appear to be feasible. The results of this project indicate that the sagged and annealed glass panels will not survive the pressure and temperature conditions (600-700 psi, 300^{o}F) encountered in SMC molding. However, the chemically strengthened glass mirrors were elastically formed to the parabolic contour and were successfully molded as an integral part of the structure. The 4 x 2 ft parabolic panels consisted of a front sheet of silvered glass molded with a back face sheet of SMC plus peripheral ribs and internal ribs for structural stiffness. Ribs were successfully molded with no "sink" evident on the reflective surface of the glass.

The environmental capability of these panels appears to be excellent based on their response to accelerated thermal cycling tests. The silver coating (including copper and protective paint) is totally encased within the SMC material for excellent weather protection. The SMC appears to bond to the protective paint.

A bimaterial effect is observed in the panels due to the difference in thermal expansion of the glass and the SMC. Upon cooling from mold temperature, the units opened up, increasing the panels' focal length. Subsequent thermal cycling produced stress relief (or annealing or creep) in the SMC and the parts closed again (focal length decreased). The stress relief response is not fully understood.

Additional development work is needed to achieve a materials/ design suitable for use in high production of solar collectors. Specific areas requiring attention are:

1. Tailoring of the SMC coefficient of expansion to match more closely that of the glass in order to minimize the bi-material effect.

2. Determination of stress profiles in the part and shear stresses at the SMC/glass interface.

3. Determination of a thermal schedule to relieve the residual stresses produced by the expansion mismatch.

4. Evaluation of deflection due to wind, gravity and daily temperature cycling.

5. Investigation of effects of molding on the silver/ glass interface and the adherence of the SMC to the protective paint or other coatings on the glass.

6. Continued environmental evaluation.

References

1. J. F. Banas, Technology Assessment: Line-Focus Concentrators, Sandia Laboratories Report SAND79-2221, January 1980.

2. K. D. Bergeron, R. L. Champion, and R. W. Hunke, Eds., Line-Focus Solar Thermal Energy Technology Development FY79 Annual Report for Department 4720, Sandia Laboratories Report SAND 80-0865, April 1980.

3. L. M. Larsen, Ed., FY78 Annual Progress Report: Midtemperature Component and Subsystem Development Project, Sandia Laboratories Report SAND79-0800, September 1979.

4. G. W. Treadwell, Design Considerations for Parabolic-Cylindrical Solar Collectors, Sandia Laboratories Report SAND76-0082, July 1976.

5. F. Biggs and C. N. Vittitoe, "Concentrator Quality Evaluation" Proc. 1978 Meeting International Solar Energy Society, American Section, Denver, CO, August 28-31, 1978, pp. 850-854.

6. B. L. Butler and R. B. Pettit, Optical Evaluation Techniques for Reflecting Solar Concentrators, Proc. 21st Symposium Soc. Photo-Optical Instrumentation Engineers, San Diego, Calif., August 22-26, 1977, paper 114-10.

7. R. B. Pettit and B. L. Butler, "Laser Ray Trace and Bi-Directional Reflectometry Measurements of Various Solar Concentrators, Proc. ERDA Concentrating Solar Collector Conference, Georgia Inst. Tech., Atlanta, GA, September 26-28, 1977, paper 6.5.

8. L. Orear, Sensitivity of Slope Measurements on Parabolic Solar Mirrors to Positioning and Alignment of the Laser Scanner, Sandia Laboratories Report SAND 78-0700, May 1978.

9. B. D. Hansche, Laser Ray Trace Tester for Parabolic Trough Solar Collectors, ISA Trans., 19, 2, 1980.

10. Gruenewald, R. and Walter, O., "Fifteen Years Experience with Sheet Molding Compound", Reinforced Plastics/Composites Institute, 30th Technical Conference, Society of the Plastics Industry, Washington, D. C., February 4-7, 1975, paper 1-C.

11. Olsen, N., Powell, R., Baker, E., "The Use of SMC in Aerodynamic Deflector", Reinforced Plastics/Composites Institute 32nd Technical Conference, Society of the Plastics Industry, Washington, D. C., February 8-11, 1977. paper 12-A.

12. "Reinforced Plastics: Making a Stronger Case Against Metals," Plastics World, 36, 6, June 1978, pp. 50 -56.

13. R. E. Allred, D. W. Miller, and B. L. Butler, Environmental Testing of Solar Reflector Structures, Proc. 1979, International Solar Energy Society Congress, Atlanta, GA, May 28 - June 1, 1979, paper F-II-C-2.

14. R. C. Reuter and R. E. Allred, Structural Optimization of Sheet Molding Compound Line Focusing Collectors, Proc. 24th National SAMPE Symposium, San Francisco, CA, May 8-10, 1979, pp. 866-877.

15. R. E. Allred, Sandia Laboratories, unpublished data.

16. T. R. Guess, R. E. Allred and F. P. Gerstle, Comparison of Lap Shear Test Specimens, J. Testing and Eval., 5, 2, 1977, pp. 84-93.

Table I

As-Molded Optical Characteristics of 4' x 2' SMC parabolic troughs

Construction		Number	Mean Focal Length(1)		Slope Error	
Rib Pattern	Surface	Specimens	Inches		mrad	
I	SMC	3	29.79	.25(2)	3.36	.22
II	SMC	2	30.11	.06	2.31	.08
I	sagged glass(3)	3	31.36	.26	1.95	.11
II	sagged glass(3)	1	31.34		1.52	
I	strengthened glass	3	31.79	.18	2.51	.49
II	strengthened glass	4	31.35	.10	2.17	.14
II	strengthened glass and 9230-30 SMC	2	31.97	.10	2.81	.20

(1) mold focal length 30.00 inches

(2) Standard deviation

(3) glass cracked

Table II

Tensile Properties of Molded Parabolas

	Modulus 10^6 psi		Ultimate Strength psi	
SMC:				
Face	1.20	.12[+]	8530	2230
Rib length	1.83	.55	11420	5930
Rib depth	1.63	.28	8990	4380
SMC w/sagged glass:				
Rib length	1.76	.17	11350	5230
Rib depth	1.70	.71	4830	1970
Flat Sheets	1.05	.32	7860	2770

[+] standard deviation

Table III

Chemical Content of Molded SMC Parabolas

Present Volume Fractions

Location	Glass		$CaCo_3$		Resin		Voids	
SMC								
Face	16.80	1.40	32.87	0.68	47.13	.64	3.20	0.10
Ribs	18.20	0.94	31.54	0.21	44.40	1.10	5.85	0.37
SMC W/Sagged Glass								
Face	19.01	0.86	31.63	0.45	46.81	0.60	2.56	0.13
Ribs	17.95	1.27	31.48	0.78	44.99	0.67	5.58	0.79

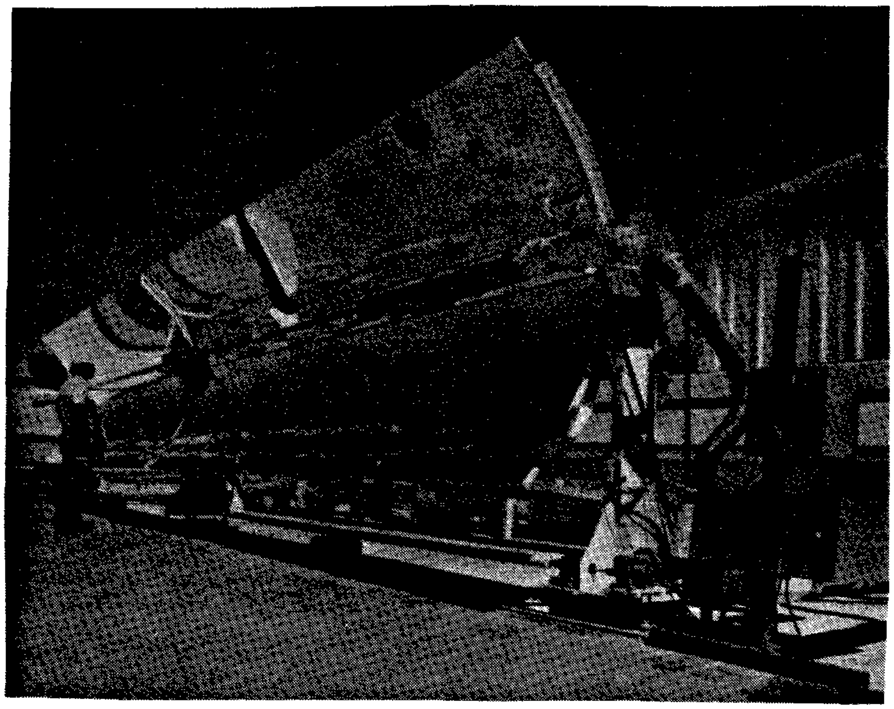

Figure 1. Parabolic Trough Collector

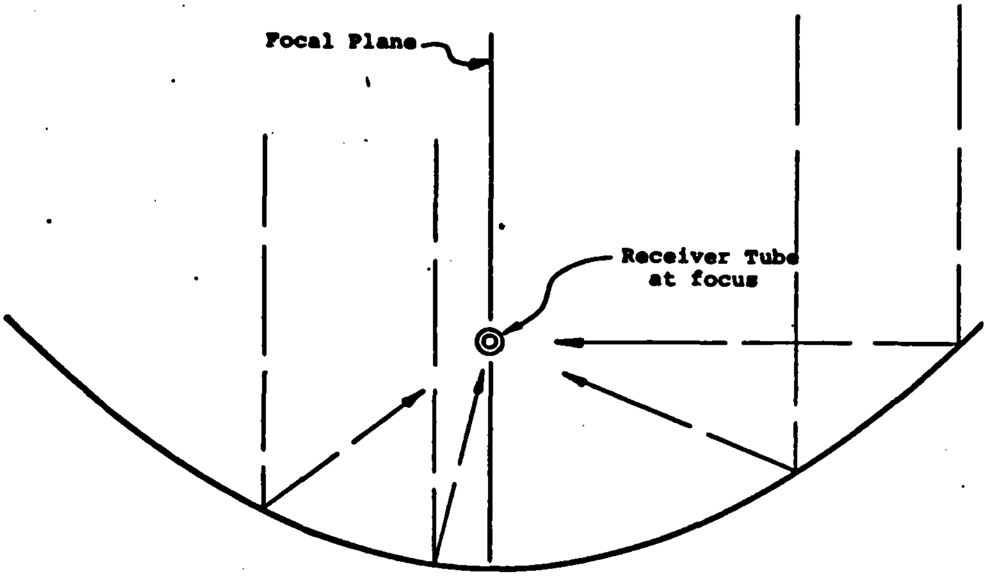

Figure 2. Parabolic Reflector

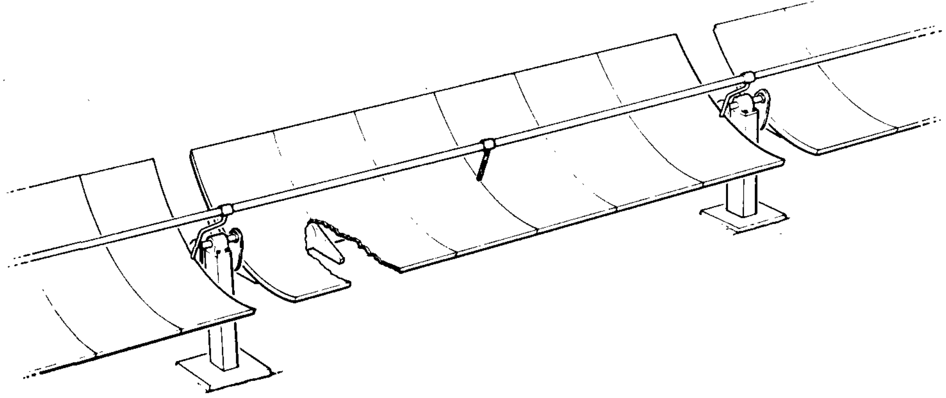

Figure 3. 2m x 6m Parabolic Trough Module Design Concept

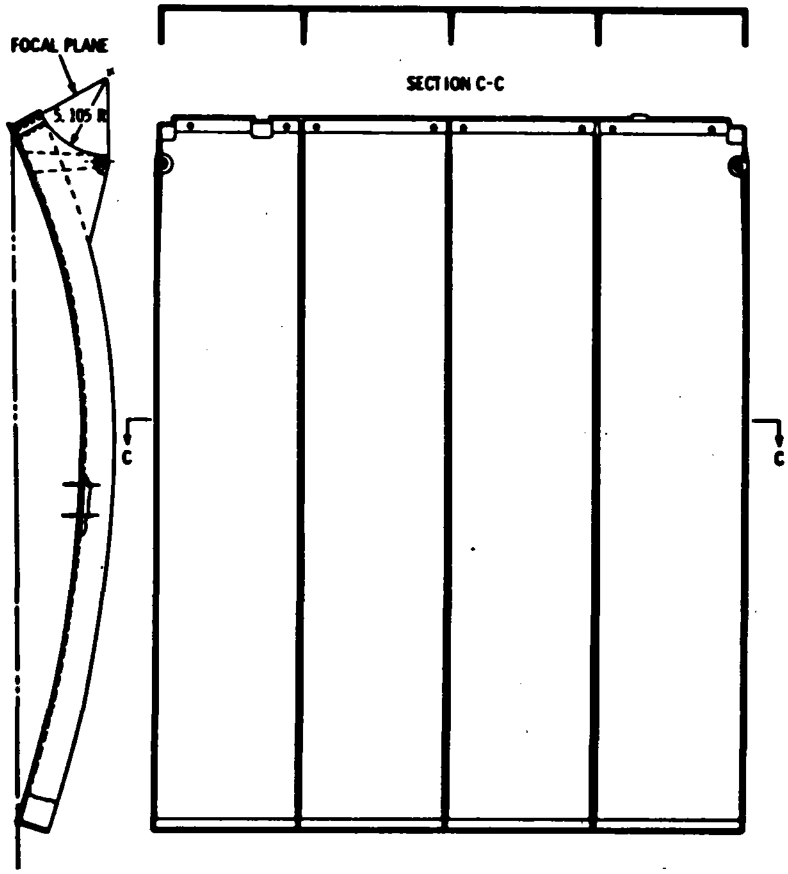

Figure 4. SMC Reflector Panel for 2m x 6m Trough

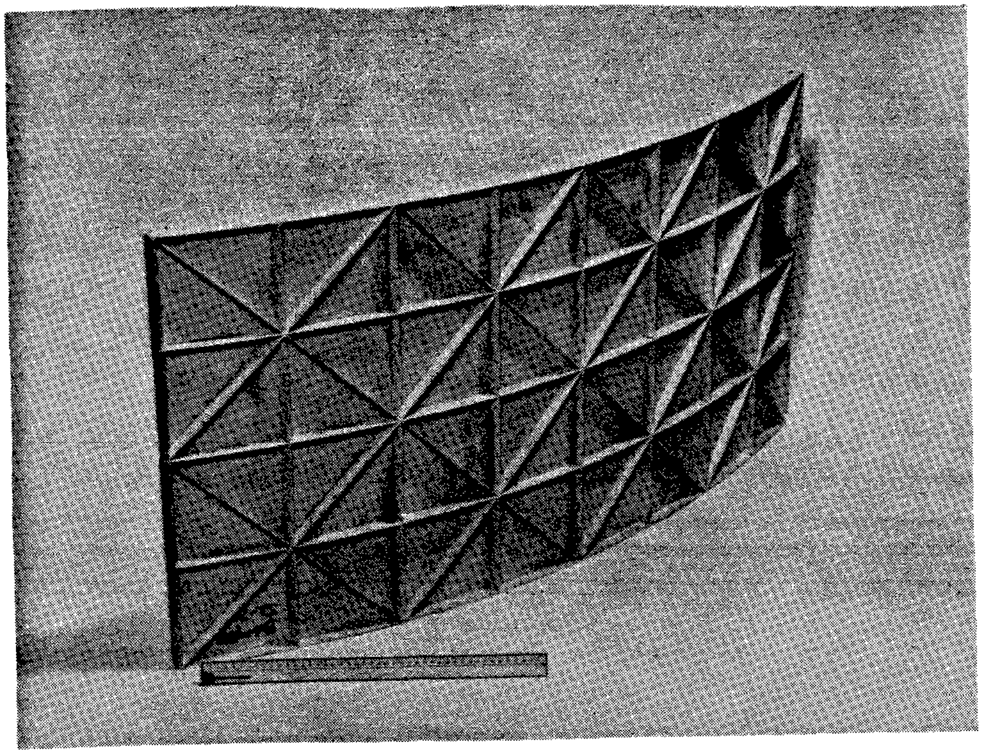

Figure 5. Early SMC Molded Reflector Panel

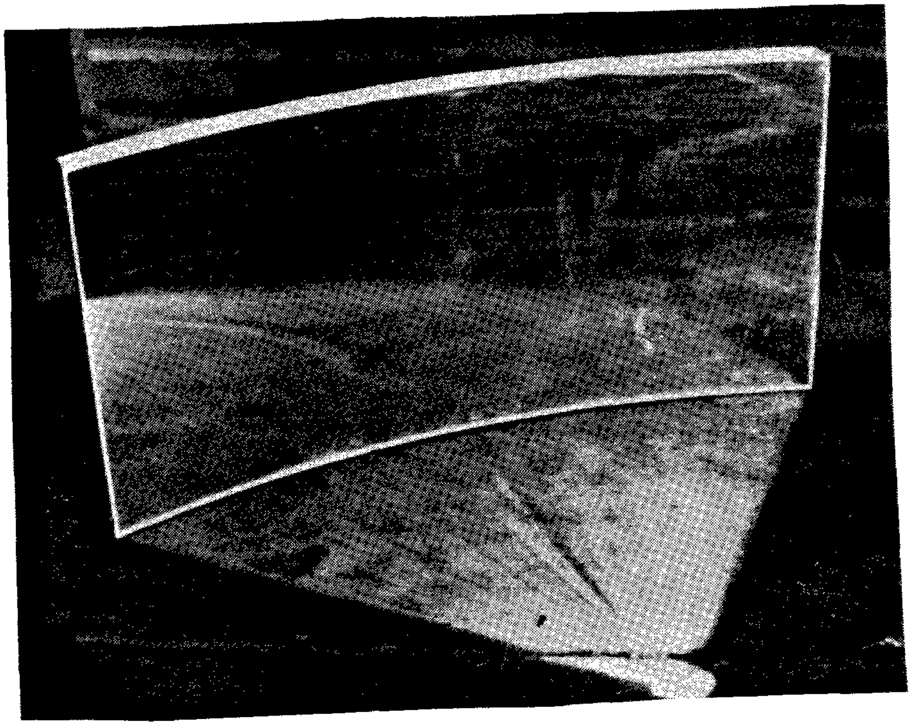

Figure 6. 2 x 4 ft SMC Panel Rib Structure

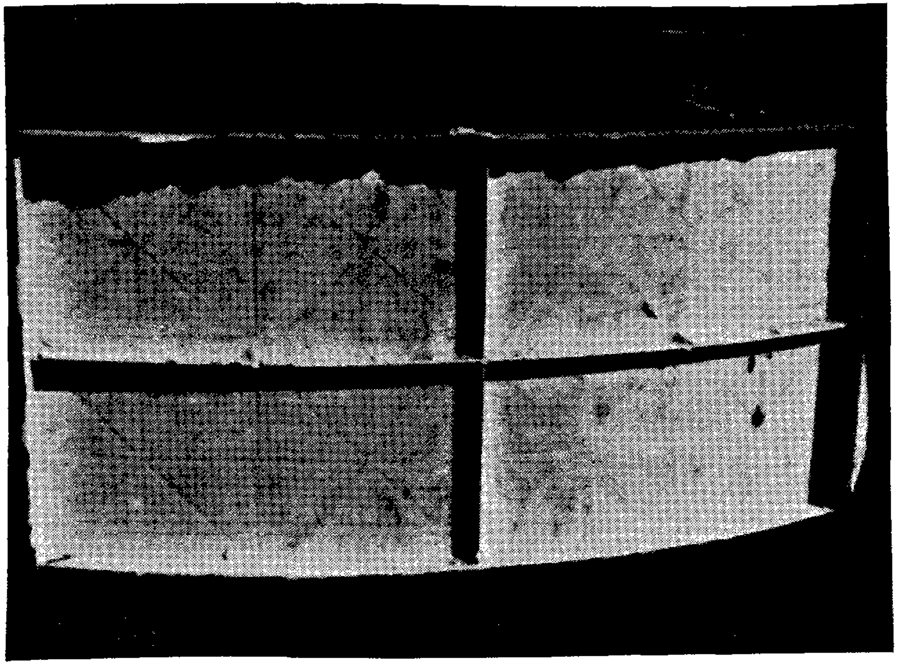

Figure 7. 2 x 4 ft SMC Panel With Molded-In Glass Reflector

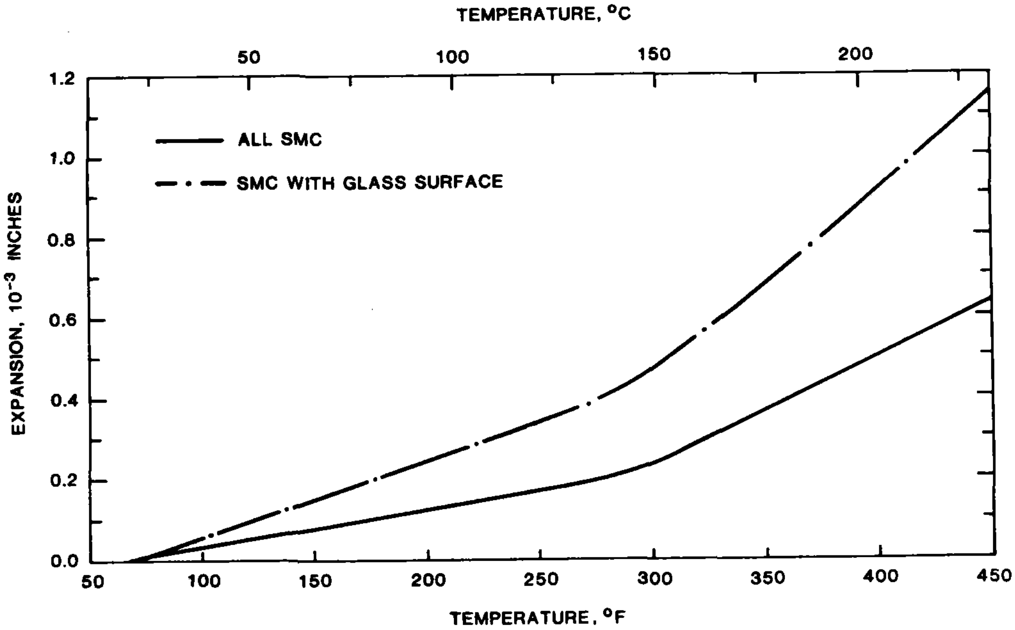

Figure 8. Transverse Thermal Expansion of SMC Panels Molded With and Without Glass Surfaces.

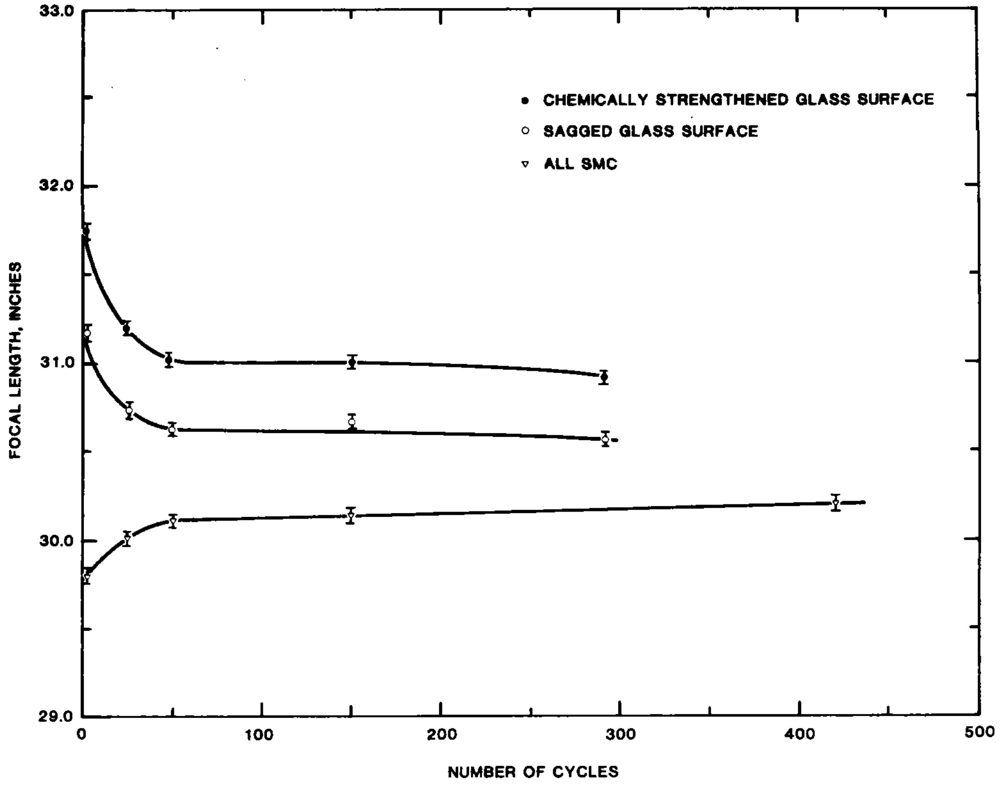

Figure 9. Change in Focal Length of Configuration I Units with Thermal Cycling

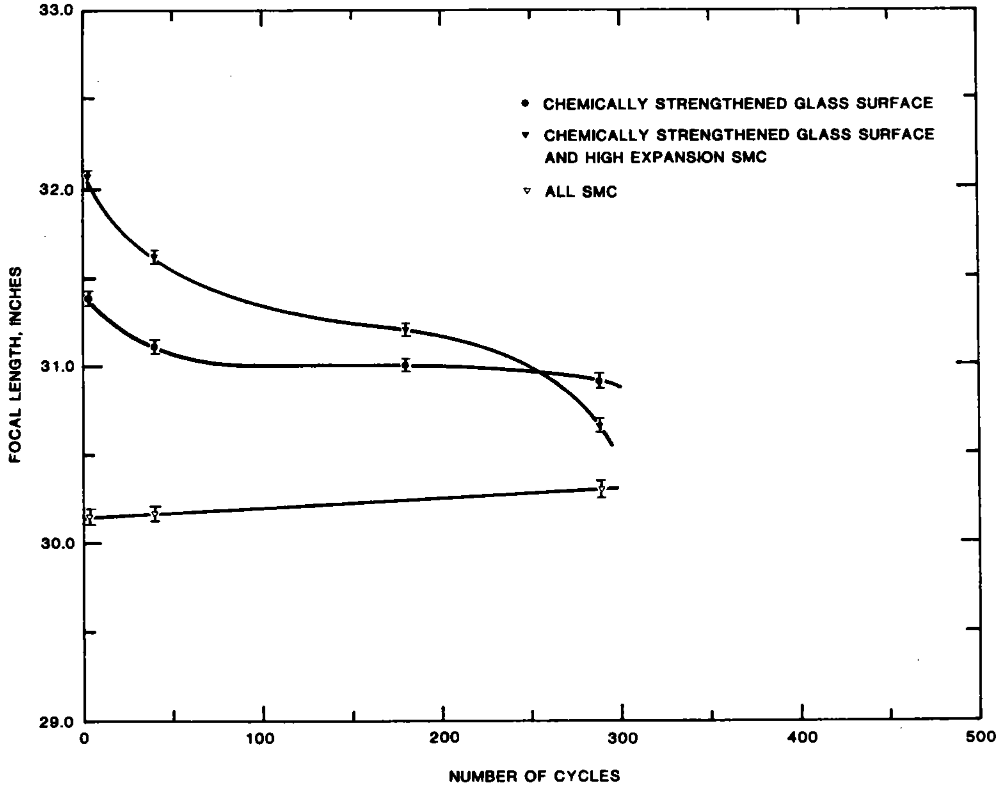

Figure 10. Change in Focal Length of Configuration II Units with Thermal Cycling

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