Sandwich Construction Solar Structural Facets

Richard B. Diver
Sandia National Laboratories
Albuquerque, NM 87185

James W. Grossman
Sandia National Laboratories
Albuquerque, NM 87185

ABSTRACT

Silver/glass mirrors have excellent optical properties but need a method of support in order to be used in concentrating solar thermal systems. In collaboration with the Cummins dish/Stirling development program, we started investigating sandwich construction as a way to integrate silver/glass mirrors into solar optical elements. In sandwich construction, membranes such as sheet metal or plastic are bonded to the front and back of a core (like a sandwich). For solar optical elements, a glass mirror is bonded to one of the membranes. This type of construction has the advantages of a high strength-to-weight ratio, and reasonable material and manufacturing cost. The inherent stiffness of sandwich construction mirror panels also facilitates large panels. This can have cost advantages for both the amount of hardware required as well as reduced installation and alignment costs. In addition, by incorporating the panels into the support structure reductions in the amount of structural support required are potentially possible.

We have investigated sandwich construction panels that employ cores of polystyrene, polyvinyl chloride (PVC) and polyurethane foams as well as conventional aluminum and cardboard honeycombs. Our investigations have involved fabricating 0.5 x 0.6-m (20 x 24-inch) spherical-contour panels and testing their optical properties and environmental durability. We have also performed preliminary cost and performance studies. Evaluations included optical testing with the SunLab "2f" and VSHOT tools both before and after exposures to environmental chamber testing. Our results showed that sandwich mirror panels are potentially very accurate. However, long-term degradation due to creep was evident in all of the foam core facets. The aluminum honeycomb core facets were accurate and durable. In this paper, the design principles that have guided our investigations, estimates of cost, and the results of our experimental investigations are presented.

INTRODUCTION

Low-cost/high-performance solar collectors are needed to make solar thermal power competitive with other fuels. Incorporation of mirrors into viable optical elements is a key to low-cost, high-performance solar concentrators and has been accomplished several ways outlined below.

Glass-foam core mirrors were developed by the Jet Propulsion Laboratory (JPL) in the 1970s and 1980s. With this construction, glass mirrors are mechanically deformed and bonded to a foamed glass support, which has been ground to the specified contour. The foam glass is intended to match the thermal expansion coefficient of the glass mirror. (Argoud, 1980)

Steel-substrate support entails glass mirrors bonded to a steel sheet, which in turn are supported by a stretch-formed or stamped steel backup structure (like a car hood). This type of support was used in the McDonnell Douglas dish concentrator. (Stone, et al., 1993) Similar approaches, but with rib supports stretch-formed or stamped to the desired curvature, were used by Acurex in their Innovative Concentrator design and by Solar Kinetics, Inc. (SKI) on the Shenandoah dishes. Both of these concentrators used reflective film. (Overly, et al., 1985, and Saydah, 1983) Fiberglass supports formed over a mandrel have been investigated recently by Kansas Structural (Gill and Plunkett, 1997) and McDonnell Douglas (NREL, 1998).

Stretched-membrane designs incorporating membranes of plastic or steel stretched over both sides of a ring have received a lot of attention. In the stretched membrane design, vacuum in the plenum between the membranes is drawn to create curvature. Examples include LaJet/Cummins facets, the SAIC USJVP dish and several heliostat designs. (Bean and Diver, 1995 and, Beninga, et al., 1989 and 1997) Stretched-membrane concentrators with plastically deformed metal membranes, for short focal length to diameter ratios, have been developed by Solar Kinetics, Inc. (Schertz et al., 1991) and Schlaich, Bergermann, und Partner. (Schlaich et al., 1994).

Mirrors constructed of laminations of thin-glass mirrors to thick-glass supports and the use of thick-glass mirrors with inherent structural capabilities have been utilized. Examples include the ATS heliostat and the Solar Electric Generator System (SEGS) troughs built by LUZ Corporation. (Gorman, et al., 1986, Pilkington, 1996)

Some of most promising early efforts to develop solar concentrator mirror facets used sandwich construction. In sandwich construction, membranes (such as sheet steel, aluminum, or plastic) are bonded to both sides of a core material. This type of construction is widely utilized in products ranging from doors and tables to aircraft and boats and is characterized by high strength-to-weight. For solar applications, glass mirrors are adhesively bonded to one of the membranes. Examples of sandwich construction mirrors include the Solar One heliostat mirrors (Stone, et al., 1993), the Solar Kinetics, Inc. Innovative Concentrator panels (Shertz, 1986), the General Electric Parabolic Dish Concentrator (the PDC-1 used a reflective film) (Sobczak, 1982), and the Cummins Utility-Scale dish concentrator. Some of the early prototype trough mirrors also used sandwich construction mirrors.

Recently, we have investigated sandwich construction panels that support silver/glass mirrors. Although a variety of reflective materials have been developed for concentrating solar power systems, silver/glass mirrors are currently the only reflective material that have been proven in long-term outdoor applications. Most of the research and development on silver/glass solar mirrors was done in the late 1970s and early 1980s. During this period silver/glass mirrors were implemented on troughs, central receivers and dishes with differing levels of success. The SERI report, "Silver/Glass Mirrors for Solar Thermal Systems," (SERI, 1985) provides a good technical summary and discussion of manufacturing methods and failure mechanisms of silver/glass mirrors.

Our primary objective is to develop a facet concept that has a reasonable material cost, is manufacturable, is durable, and has good optical characteristics. Our investigations have for the most part been limited to 0.4 x 0.6 m (20 x 24-inch) samples with spherical curvatures. Optical characteristics have been evaluated with the SunLab color "2f" tool and the Video Scanning Hartmann Optical Test (VSHOT). Durability was determined by optical characterization both before and after environmental testing. Most of our efforts have focused on identifying a suitable core material and evaluating manufacturability issues. Core materials that we have tried include polystyrene, polyurethane, and polyvinyl chloride (PVC) foams, and cardboard and aluminum honeycomb. This paper summarizes the design principles that have guided our investigations and presents and discusses approaches that have and have not worked.

STRUCTURAL FACET BASICS

A schematic illustrating the construction of a sandwich-construction structural facet is illustrated in figure 1. The facet is a sandwich consisting of a glass mirror bonded to a carbon-steel sheet, a core material, and a carbon-steel back membrane (same gauge as the front membrane). Carbon steel sheets with surface treatments such as electro-galvanizing are low cost, provide corrosion resistance, and enhance adhesion. Facets with this type of laminated construction, i.e., where the mirrors is bonded to an impermeable layer with an

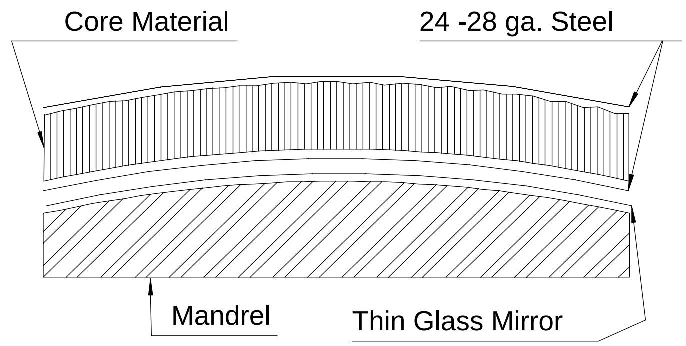

Figure 1 View of mirror assembly.

adhesive transfer tape, have demonstrated excellent durability in the field. (Stone, et al., 1993, Diver, et al., 1995) This construction prevents water (an electrolyte) from coming in contact with the painted silver surface, and thereby prevents electrochemical corrosion, which is the principal corrosion mechanism for silver/glass mirrors. Bonding the entire mirror surface to the steel maintains the integrity of the mirror if it breaks, therefore allowing it to continue to function safely. The steel sheets and core are adhesively bonded over a mandrel of the desired curvature (for focusing the sunlight). Vacuum bagging is used to provide uniform loads during the adhesive cure. Two part adhesive systems such as epoxy or acrylic, with working times of 10-90 minutes are used. The adhesive bonds between the steel sheet and core "lock-in" the mandrel's curvature.

The use of two steel membranes is key to the thermal stability of this construction and maintaining good optical characteristics over a range of ambient temperatures. First, the thermal expansion coefficient of steel (typically about 10.8 – 12.6 x10^{-6} m/m^{o}C (6–7 x10^{-6} in/in ^{o}F)) is a good match to glass (5.4 – 12.6 x10^{-6} m/m^{o}C (3-7 x10^{-6} in/in ^{o}F), depending on composition). By contrast, the expansion coefficient of aluminum alloys (approximately 21.6 x10^{-6} m/m^{o}C (12 x10^{-6} in/in ^{o}F) and plastics (45 – 54 x10^{-6} m/m^{o}C (25-30 x10^{-6} in/in ^{o}F)) are much higher than that of glass. The relatively close thermal-expansion-coefficient match of steel and glass minimizes thermally induced stresses and optical distortions. Second, the relatively high elastic modulus of steel, approximately 207,000 MPa (30x10^6 psi) vs. 69,000 MPa (10x10^6 psi) for glass, assures that the sandwich structure dominates the glass and maintains the shape as ambient temperature changes. Third, steel skins on the front and back of the sandwich compensate for each other and, therefore, also minimize changes in curvature with changes with temperature.

Sandwich construction results in facets with excellent mechanical and optical properties. Structurally, sandwich panels are similar to I-beams. The membrane sheets of the panel are like the flanges of an I-beam, and the core corresponds to the web. However, unlike an I-beam, the core gives continuous support to the facing sheets. The continuous support for the membrane is important for maintaining the optical characteristics needed for concentrating solar collector mirrors. The structural benefits of sandwich construction optical elements have been known for many years. Analytical studies of the structural characteristics of aluminum honeycomb troughs indicate excellent characteristics. For example, Koteras (1980) concluded that a 2.54-cm

(1-inch) thick aluminum-honeycomb parabolic trough mirror with a 2-meter (6.6-foot) aperture could provide adequate support over spans of six meters (twenty feet) in winds of up to 40.23 m/sec (90 mph). In similar analytical studies, we determined that a flat 1.22 meter x 2.44 meter (4 ft x 8 ft) heliostat mirror panel constructed with 26-gage steel facings and a 2.54-cm (1-inch) thick polystyrene core would experience insignificant deflections facing into winds up to 18 m/sec (40 mph). We experimentally determined that the calculations were conservative.

STRUCTURAL FACET COST

For the purpose of evaluating cost, we have divided cost into material cost and manufacturing cost. Material cost represents a fundamental limitation to how inexpensive a component can be made and is easily quantified. Because of the use of commonly used materials, material costs are reasonable for structural facets. In small quantity purchases, material cost for our highest performance samples were about \$56.5/m^2 (\$5.25/ft^2). In quantity, depending on the application and the choice of mirror, core and adhesive options, material cost for structural facets could be as little as \$26.9/m^2 (\$2.50/ft^2).

Manufacturing costs are a function of production levels, tooling and the amount of labor and are difficult to quantify. Typically, however, the cost of items manufactured at high volumes with minimal labor approach material cost for many common items. Development of an approach that is readily capable of being automated is, therefore, key to low manufacturing cost. Exploration of the applicability of industry standard practice to a non-standard industry product (solar mirrors) was an important element of our studies.

There are other potential cost advantages of structural facets that require consideration of the system. The ability to make structural facets in large sizes reduces the amount of support structure required. This can reduce the amount of mounting structure and hardware and installation costs. For some concentrators, mounting structure is more expensive than the optical elements. Reductions in structure required by the use of large optical elements or by incorporating them into the structure could significantly reduce concentrator cost.

FABRICATION TECHNIQUES

We have employed two techniques for fabricating sandwich-construction structural facets – vacuum bagging and foam-in-place. In vacuum bagging, the glass/steel laminate is laid mirror surface down onto a mandrel. Adhesive is applied to the back of the glass/steel laminate and to one side of the back steel skin. A core material is placed between the steel skins in contact with the adhesive. The sandwich is then covered with and sealed inside a plastic sheet and a vacuum is applied. Atmospheric pressure applies a high and uniform clamping force to the sandwich, which forces the steel and glass sheets to conform to the mandrel. Vacuums range from 381 to 584 mm of mercury (15 to 23 inches of mercury), depending of how well the bag is sealed. After the adhesive has cured, the curvature of the mandrel is locked into the sandwich. Because of the prohibitive cost of mandrels and the long cure times required, we evaluated the affect of stacking on optical accuracy. The ability to manufacture optical elements from secondary mandrels is a key to reducing manufacturing costs.

The foam in place technique was performed exclusively with two-part urethane foams. We used a North Carolina Foam Industries, Inc. pour-in-place system (#811-91). Typical foam density ranged from about 70.4 kg/m^3 to 83.3 kg/m^3 (4.4 to 5.2 lb/ft^3) and was inversely proportional to cure temperature. With this technique, the glass/steel laminate is laid mirror surface down on the mandrel, as in the vacuum bag technique. The two-part urethane foam is then mixed, poured, and spread onto the back of the steel sheet. The back steel sheet is then placed directly onto the foam. A frame spaced at a set distance from the mandrel holds the back steel sheet in place as the foam expands and forces the foam to ooze from the sides of the sandwich. The expanding foam forces the glass/steel laminate to conform to the mandrel. After the foam cures, the curvature of the mandrel is locked into the sandwich. The frame is then removed and the excess foam is trimmed from the edges.

RESULTS

Our investigations were primarily experimental and were conducted over several years. Except for a few special builds, our experiments were all with 0.5 x 0.6-m (20 x 24-inch) samples formed over spherical mandrels. The radii-of-curvatures of the mandrels were 10.668, 13.208, and 15.748 meters (420, 520, and 620 inches). The facets fabricated and tested are summarized in Table 1. At first optical characteristics were evaluated with the SunLab color “2f”. (Grossman and Edgar, 1996) Eventually, the Video Scanning Optical Test (VSHOT) was used. (Jones, et al., 1997) Comparisons (Wendelin and Grossman, 1995) indicated that measurements with the “2f” tool were comparable to the VSHOT.

Durability was determined by optical characterization both before and after environmental testing. Environmental testing was intended to evaluate structural and optical degradation from exposure to the environment. Silver corrosion and degradation was not an issue of interest. Tests ranged from exposure to elevated temperatures (>50^{o}C) to thermal cycling with high humidity. Most of our efforts were focused on identifying a suitable core material and understanding degradation mechanisms.

Core materials that we evaluated include polystyrene, polyurethane, and polyvinyl chloride (PVC) foams, and cardboard and aluminum honeycomb. Core materials of polystyrene and urethane foams were found to be unstable at elevated temperatures (>50^{o}C). Figure 2 shows typical results from “2f” testing of a Dow extruded polystyrene foam. In this test, a facet was exposed to 51^{o}C (124^{o}F) and periodically evaluated. The “2f” results clearly indicate that the facet’s focal length and slope error increased with time. A facet with the same construction exhibited minimal change when exposed to –23^{o}C (-10^{o}F). We theorize that the stresses induced by the elastically deformed flat steel and glass mirror caused the foam to creep. The “2f” results indicate approximately 0.45 meters (18 inches) of initial “spring back” from the 13.208-m (520- inch) radius-of-curvature mandrel.

PVC (Klegecell) foam mirror modules were utilized by Cummins in their 25-kWe Utility-Scale Joint Venture Program (USJVP) concentrator. The Cummins facets used a 3.18-cm (1-1/4-inch) thick 75 kg/m^2 (4.68 lb/ft^3) PVC foam that was kerfed (sliced most of the

Table 1 - Structural Facet Summary

Series Number Dates	Steel Cost	Adhesive Costs	Core/Cost	Total Cost*	Fabrication technique	Typical Slope Error (mrad)	Comments
S 10 11/95 –4/96	24-26 gage Paint-lok $1.00/ft^2$ $10.80/m^2$	Mac Tac /epoxy $0.80/ft^2$ $8.60/m^2$	Dow Blue board $0.40/ft^2$ $4.30/m^2$	$3.64/ft^2$ $39.16/m^2$	Vacuum Bag	0.6-0.8 "2f"	Blue board creeps at elevated temperatures. Potentially suitable for heliostats.
S 5 2/96	24-26 gage Paint-lok $1.00/ft^2$ $10.80/m^2$	Mac Tac /epoxy $0.80/ft^2$ $8.60/m^2$	Klegecell (PVC) $3.00/ft^2$ $32.28/m^2$	$6.24/ft^2$ $67.14/m^2$	Vacuum Bag	0.5-0.7 "2f"	Expensive but more thermally stable option than other foams. Used by Cummins.
F 20 6/96-5/97	24-26 gage Paint-lok $1.00/ft^2$ $10.80/m^2$	Mac Tac $0.44/ft^2$ $4.73/m^2$	Urethane Foam $0.55/ft^2$ $5.92/m^2$	$3.43/ft^2$ $36.91/m^2$	Foam-in-place	0.6-0.8 VSHOT	Mechanically unstable. Thermal cure or other foams may be suitable.
A 22 10/97-5/98	26 gage Paint-lok $1.00/ft^2$ $10.80/m^2$	Mac Tac /epoxy $0.80/ft^2$ $8.60/m^2$	1x3/8 in Al Honeycomb $2.00/ft^2$ $21.52/m^2$	$5.24/ft^2$ $56.38/m^2$	Vacuum Bag	0.4 - 1 VSHOT	Only thermally stable core material found.
C 2 6/98	26 gage Paint-lok $1.00/ft^2$ $10.80/m^2$	Mac Tac /epoxy $0.80/ft^2$ $8.60/m^2$	1x3/8 in Paper Honeycomb $0.50/ft^2$ $5.38/m^2$	$3.74/ft^2$ $40.24/m^2$	Vacuum Bag		Not stable.
Production Scenario 1 (Troughs)	26 gage Paint-lok $0.760/ft^2$ $8.18/m^2$	Mac Tac/epoxy $0.60/ft^2$ $6.46/m^2$	3/8x3/8-in Al Honeycomb $0.53/ft^2$ $5.70/m^2$	$3.18/ft^2$ $34.22/m^2$	Vacuum Bag		
Production Scenario 2 (Dishes)	26 gage Paint-lok $0.76/ft^2$ $8.18/m^2$	Mac Tac/epoxy $0.60/ft^2$ $6.46/m^2$	1/2x3/8-in Al Honeycomb $0.70/ft^2$ $7.53/m^2$	$3.28/ft^2$ $35.29/m^2$	Vacuum Bag		

* Includes mirror cost. Mirrors used for the 0.5x 0.6 m (20x24 inch) samples were 1.1-mm float glass and cost $15.59/m^2 ($1.44/ft^2). Mirror cost range from about $7.53/m^2 ($0.70/ft^2) for single strength 2.2 mm (3/32-inch) float glass mirrors purchased in large quantities to over $43/m^2 ($4.00/ft^2) for low-iron mirrors in small quantities. Production costs assume mirrors at $13.45/m^2 ($1.25/ft^2) for 1-mm low-iron mirrors in large quantities. Cost of paint, mounting and edge close-out are not included.

way through the foam, in both directions) to reduce bending resistance. We experimentally determined that facets made with un-kerfed material had low slope errors (about 0.5 mrad) and minimal spring back. The Cummins facets also passed hail gun test with 2.54 cm (1-inch) ice balls at 22.5 m/sec (50 mph). However, the PVC foam facets focal length increased when exposed to elevated temperatures, although to a much lesser degree than the polystyrene foam.

Urethane foam core facets appear to be an attractive approach. Urethane foam is inexpensive and provides adhesion to the steel membranes, resulting in low material cost. In addition, urethane foams have short cure times (less than 30 minutes is feasible), permitting rapid production. Reaction injection molding also lends itself to mass production. Unfortunately, we were unable to demonstrate optically stable urethane foam-core mirrors. Although typical slope errors were about 0.5 mrad shortly after manufacture, exposure to even mildly elevated temperatures caused slope errors and focal length to increase in relatively short periods of time. In some facets we measured degradation over a period of months, even when facets were stored at ambient temperatures. The optical degradation of urethane foam facets was more severe than the polystyrene core facets. While the polystyrene core facets generally relax, resulting primarily in a longer focal length, the urethane foam facet optical degradation was more random in nature. Apparently, curing rates and, therefore, density, and mechanical properties within the foam vary greatly. Even though urethane foams are reported to be usable at higher temperatures and are supposed to be more resistant to creep than polystyrene foams, these property variations have detrimental effects on the facet's optical characteristics over time. It is possible, however, that other foam formulations or the use of a high-temperature cure to anneal the foam could help to stabilize the foam properties.

Facets made from paper honeycomb were unable to maintain good optical characteristics over time. Results with aluminum honeycomb, however, were excellent. Slope errors were less than 0.5 mrad and spring back was minimal. More importantly, minimal optical degradation resulted from environmental testing. Environmental testing consisted of 100 cycles between –28^{o}C and 66^{o}C (-20^{o}F and 150 ^{o}F) with 4-hour ramps and 2-hour holds at temperature. High humidity (80%) was applied at the high-temperature condition. Although some edge degradation occurred on a facet with no edge protection, there was no evidence of change in focal length or degradation of optical characteristics inside approximately 2 cm (0.78 in) from the edge. No degradation was

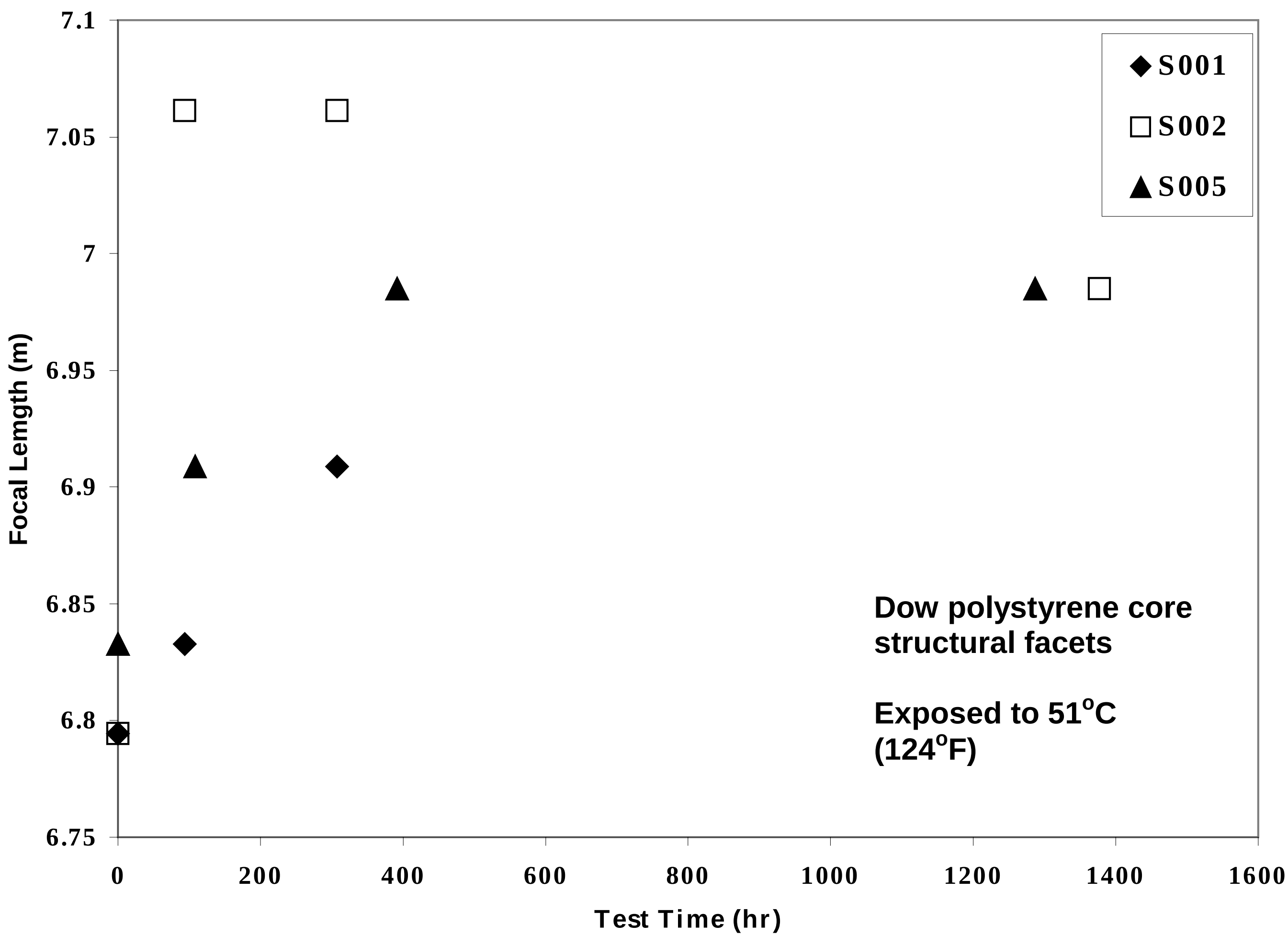

Figure 2. Color "2f" results showing creep of three Dow polystyrene core facets exposed to elevated temperature.

measured on a facet that used aluminum foil tape to close-out the aluminum honeycomb.

Tests were conducted to determine the optical characteristics of facets formed on the back of other facets, instead of directly off of the mandrel. For the 2.54-cm (1-inch) thick by 0.95-cm (3/8-inch) diameter cell aluminum honeycomb formed over the 10.668-m (420-inch) radius-of-curvature mandrel, the forces from vacuum bagging were insufficient to overcome the rigidity of the aluminum honeycomb. Slope errors of six facets formed at the same time ranged from 2.5 to 3.5 mrad. VSHOT vector plots showed most of the optical errors were at the outside 8 to 10 cm (3.1 to 4 inches) of the facets, and suggest insufficient vacuum to force the edges of the facets to the mandrel. VSHOT plots and measurements of the inner 12 x 14 inches of the facet show a range of slope errors near 1.0 mrad and a slight progression in slope error from the bottom to the top of the stack. Fabrication of two facets on a mandrel resulted in facets with slope errors of about 0.9 mrad with negligible spring back. These results suggest limitations in the number of facets that can manufactured at a time, and quantify optical accuracy reduction with each mirror layer, at least for this set of parameters. These results indicate that it should be feasible to produce at least two facets in each vacuum bagging operation and that the use of secondary mandrels is feasible. Both of these factors suggest that manufacture of mirror modules can be automated.

SUMMARY

Low-cost/high-performance solar collectors are needed to enable commercial solar thermal power systems and sandwich construction structural facets appear to be a good candidate for producing viable mirror modules for concentrating solar power systems. Furthermore, we believe that integration of glass mirrors with the structural capabilities of sandwich construction can provide additional benefits.

In our attempt to identify low-cost constructions we have tried to take advantage of the lessons learned over the past 20 years while following basic engineering principles. For example, the use of proven silver/glass mirrors has dictated the use of steel membranes. Although our investigations have led to many approaches that don't work, we have identified at least one mirror concept that is accurate, durable, robust, reasonable cost, and manufacturable.

These investigations have been exploratory in nature and much needs to be done. Despite our inability to demonstrate a stable foam core facet, we believe that this remains a potentially attractive option. Efforts to identify alternative foams or modification or optimization of the manufacturing process and/or design parameters could be worthwhile. In addition, concentrator designs that capitalize on the inherent structural capability of sandwich construction facets should be developed and proven. Ultimately, manufacture of large quantities of structural facets for troughs, dishes, and/or heliostats is needed to reduce cost and prove the approach under realistic conditions.

ACKNOWLEDGMENTS

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the U.S. Department of Energy under Contract DE-AC04-94-AL85000. The authors would like to thank Tim Wendelin (NREL), Scott Jones and Dick Houser (Sandia) for VSHOT and environmental test support; Pete Rand and Brad Hance (Sandia) for help with foams; Scott Rawlinson (Sandia) for structural analysis; and Tim Moss and Daniel Ray (Sandia) for assistance with mandrels and vacuum equipment.

REFERENCES

Argoud, M.J., 1980, "Test Bed Concentrator Mirrors," Proceedings of the First Semiannual Distributed Receiver Systems Program Review, DOE/JPL-1060-33, Pasadena, CA.

Bean, J.R., Diver, R.B., 1995, "Technical Status of the Dish/Stirling Joint Venture Program," Proceedings of the 30th Intersociety Energy Conversion Engineering Conference, Paper Number 95-202, Orlando, FL.

Beninga, K., Butler, B., Sandubrae, J., Walcott, K., 1989, "An Improved Design for Stretched-Membrane Heliostats," SAND89-7027, Albuquerque, NM.

Beninga, K, Davenport, R.L., Sellars, J.A., Smith, D., Johansson, S., 1997, "Performance Results for the SAIC/STM Prototype Dish/Stirling System," Proceedings of the 1997 ASME International Solar Energy Conference, Washington, D.C.

Diver, R.B., Jones, S., Robb, S., Mahoney, A.R., 1995 "The Lustering of TBC-2," SAND94-1832, Sandia National Laboratories, Albuquerque, NM.

Gill, S.R., Plunkett, J.D., 1997, "Fabrication of Four focusing Solar Collector Segments of Widely Differing Geometries From Fiber-Reinforced Polymer Honeycomb Composite Panels," Final Report Submitted to Sandia National Laboratories, Albuquerque, NM.

Gorman, D.N., Halford, J.G., and Thomas, R.J., 1986, "Large Glass/Metal Heliostat Development," Proceedings of the Solar Thermal Technology Conference, Diver, R.B. (ed.), SAND86-0536, Sandia National Laboratories, Albuquerque, NM.

Grossman, J. W. and Edgar R. M., 1996, "Transforming the Sandia 2*f* Optical Performance Measurement System to Color," Solar Engineering 1996, ASME.

Jones, S.A., Gruetzner, J.K., Houser, R.M., Edgar, R.M., Wendelin, T.J., 1997, "VSHOT Measurement Uncertainty and Experimental Sensitivity Study," Proceedings of the 32nd Intersociety Energy Conversion Engineering Conference, Honolulu, HI.

Koteras, J.R., 1980, "Analytical Studies of a Parabolic Line Concentrator Utilizing an Aluminum Honeycomb Support Structure and a Thin Glass Reflector Laminate," SAND80-1585, Sandia National Laboratories, Albuquerque, NM.

NREL Final Report, 1998, "Solar Thermal Component Manufacturing for Near-Term Markets," Subcontract ZAP-5-15299-02, Golden, CO.

Overly, P.T., Dehne, H.J., Duffy, D.R., and Nering, E.A., 1985, "Innovative Point Focus Solar Design, Task 1, 2a, Topical Report," DOE-AL/23711-1, Albuquerque, NM.

Pilkington, 1996, "Status Report on Solar Thermal Power Plants," Pilkington Solar International GmbH, Cologne, Germany.

Saydah, A.R., Koenig, A.A., Lambert, R.H., Kugath, D.A., 1983, "Final Report on Test of STEP Shenandoah Parabolic Dish Solar Collector Quadrant Facility," SAND82-7153, Sandia National Laboratories, Albuquerque, NM.

Schertz, P.T., 1986, "Design of a Point-Focus Concentrator," Proceedings of the Solar Thermal Technology Conference, Diver, R.B. (ed.), SAND86-0536, Sandia National Laboratories, Albuquerque, NM.

Schertz P. E., P. T., Brown, D. C. Konnerth III, A., 1991, "Facet Development for a Faceted Stretched-Membrane Dish by Solar Kinetics, Inc.," SAND91-7009, Sandia National Laboratories, Albuquerque, NM.

Schlaich, J., Bergermann, R., Schiel, W., 1994, "Solar Stretch," *Civil Engineering*.

Sobczak, I.F., Pons, R.L., Thostesen, T., 1982, "Development Status of The PDC-1 Parabolic Dish Concentrator," Parabolic Dish Solar Thermal Power Annual Program Review Proceedings, DOE/JPL-1060-52, Pasadena, CA.

Solar Energy Research Institute (SERI), 1985, "Silver/Glass Mirrors for Solar Thermal Systems," SERI/SP-271-2293, Solar Energy Research Institute, Golden, CO.

Stone, K.W., Radtke, C.W., Blackmon, J.B, 1993, "Status of Glass Reflector Technology for Heliostats and Concentrators," Proceedings of the 28th Intersociety Energy Conversion Engineering Conference, Atlanta, GA.

Wendelin, T.J., Grossman, J.W., 1995, "Comparison of Three Methods for Optical Characterization of Point-Focus Concentrators," Solar Engineering 1995, Volume 2, ASME.