(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
1 March 2012 (01.03.2012)

PCT

(10) International Publication Number
WO 2012/024738 A1

(51) International Patent Classification:
F24J 2/10 (2006.01) *G02B 5/10* (2006.01)

(21) International Application Number:
PCT/AU2011/001104

(22) International Filing Date:
26 August 2011 (26.08.2011)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
2010903835 26 August 2010 (26.08.2010) AU

(71) Applicant (*for all designated States except US*): THE AUSTRALIAN NATIONAL UNIVERSITY [AU/AU]; Acton, ACT 2601 (AU).

(72) Inventors; and
(75) Inventors/Applicants (*for US only*): LOVEGROVE, Keith [AU/AU]; 12 Hamersley Place, Fisher, NSW 2611 (AU). JOHNSTON, Glen Harvey [AU/AU]; 104 The Mountain Road, Bungendore, New South Wales 2621 (AU). BURGESS, Gregory John [AU/AU]; 65 Onkaparinga Crescent, Kaleen, ACT 2617 (AU).

(74) Agent: SPRUSON & FERGUSON; GPO BOX 3898, Sydney, New South Wales 2001 (AU).

(81) Designated States (*unless otherwise indicated, for every kind of national protection available*): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PE, PG, PH, PL, PT, QA, RO, RS, RU, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States (*unless otherwise indicated, for every kind of regional protection available*): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:

— *with international search report (Art. 21(3))*

(54) Title: MIRROR PANELS FOR LARGE AREA SOLAR CONCENTRATORS

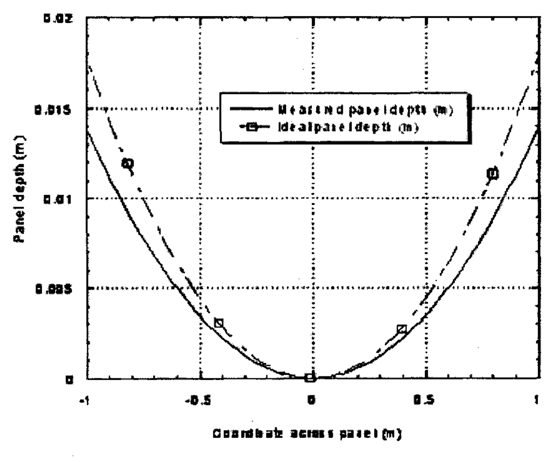

Figure 20. Plot showing the relative depth coordinate deviations between the measured paraboidal data and an ideal paraboloid (f=14 m) based on data in Fig. 19

(57) Abstract: A solar mirror sandwich panel (2000) is disclosed, comprising a reflective lamina component (2002) having a reflective surface that has an average slope error of less than or equal to about 6 milliradians, two metal skin components (2004, 2005) for stiffening the solar panel, and a core filler component (2003) disposed between the metal skin components (2004, 2005), wherein said components are bonded together using adhesive (2001) and are arranged in a curved configuration to provide a curved solar panel.

WO 2012/024738 A1

MIRROR PANELS FOR LARGE AREA SOLAR CONCENTRATORS

Reference to Related Patent Application(s)

This application claims the benefit under 35 U.S.C. §119 of the filing date of Australian Patent Application No. 2010903835, filed 26 August 2010, hereby incorporated by reference in its entirety as if fully set forth herein.

Technical Field of the Invention

The present invention relates generally to solar thermal power stations and, in particular, to solar concentrators for such power stations.

Background

Concern about greenhouse gas emissions and consequent climate change is increasing. There is, as a result, growing recognition of the importance of solar power as a major source of energy. In order for solar power to play this role however, a number of requirements need to be met. One of these requirements is for light weight, reliable solar concentrators.

Summary

Disclosed are arrangements that address the above requirements, by affixing reflective mirror panels to a sandwich panel comprising a relatively light weight core sandwiched between two or more metal skins. The sandwich panel exhibits the desired rigidity by virtue of the fact that if the panel is flexed in one direction, one metal skin experiences a tensile force and the other metal skin experiences a counteracting compressive force, these countervailing forces acting against each other in a roughly equal and opposite manner to impose rigidity on the panel. Flexing the panel in the other direction causes the metal skins to exchange the aforementioned roles, still however imposing rigidity on the panel. Selection of suitable core filler material results in light weight construction which, together with the aforementioned rigidity, provides light-weight stable reflective panels.

According to a first aspect of the present disclosure, there is provided a mirror panel comprising a lightweight rigid core, a thin metal skin on opposite sides of the core, to provide structural rigidity, and a reflective mirror surface formed on the anterior side of one of the metal skins.

According to another aspect of the present disclosure, there is provided a solar mirror sandwich panel, comprising: a reflective lamina component having a reflective surface that has an average slope error of less than or equal to about 6 milliradians and preferably less than 2 milliradians; two metal skin components for stiffening the solar panel, and a core filler component disposed between the metal skin components; wherein said components are bonded together using adhesive and are arranged in a curved configuration to provide a curved solar panel.

According to another aspect of the present disclosure, there is provided a method of making a solar mirror panel, the method comprising the steps of: providing an assembly comprising a reflective lamina component having a reflective surface, two metal skin components, a core filler component located between the metal skin components, and adhesive materials disposed between said components; conforming the components to a mould having an at least partially curved surface in contact with said components, and controllably heating at least part of at least one surface of the mirror panel to heat the adhesive material disposed between the core filler component and each of the reflective lamina component and the metal skin components, without heating the bulk mass of the core filler component.

Mirror panels manufactured in this way can be of any perimeter shape, including but not limited to triangles, trapeziums and squares.

Other aspects of the invention are also disclosed.

Brief Description of the Drawings

At least one embodiment of the present invention will now be described with reference to the drawings and the Appendices, in which:

Fig. 1 depicts a cross section of sheet metal + EPS sandwich panel (not to scale);

Fig. 2 shows an example of a process 200 for fabricating a solar panel using transient thermal bonding of EPS foam cored panels;

Fig. 3 shows a plot of areal cost vs. tensile stiffness for a range of possible skin materials;

Fig. 4 shows a plot of areal cost vs. E.t2 (a measure of flexural rigidity) for a range of possible filler materials;

Fig. 5 depicts a cross-section through double sheet metal skinned, polystyrene foam filled panel;

Fig. 6 depicts an equilateral triangular mirror panel constructed of 3 identical short isosceles triangles;

Fig. 7 depicts an equilateral triangular mirror panel constructed of 3 identical trapezoids;

Fig. 8 depicts an equilateral triangular mirror panel constructed of 3 identical trapeziums;

Fig. 9 shows deflection tests for a 1.2 m x 1.2 m dual skin, foam core panel;

Fig. 10 shows a comparative view of a hand-made trapezoidal sub-panel;

Fig. 11 shows a contour plot of a flux distribution;

Fig. 12 depicts a foam-filled dual metal skin trapezoidal mirror panel with out-of-phase trapezoidal metal substrates;

Fig. 13 depicts a lay-up of a foam-filled metal skinned panel, showing front and rear metal skins, foam core and mirrored glass laminated onto the front metal skin;

Fig. 14 shows a front view of a foam-filled mirror panel triangular prototype;

Fig. 15 shows a rear view of the foam-filled mirror panel of Fig. 14;

Fig. 16 shows an edge view of a foam-filled mirror panel, showing mirrored glass, folded sheet-metal edges and foam core;

Fig. 17 depicts predicted surface deflection characteristics for the foam-filled mirror panel;

Fig. 18 depicts a layout of approximately 1200 data points used for photogrammetric analysis of the foam mirror panel surface quality;

Fig. 19 shows a contour plot of the foam mirror panel (of Fig. 14) surface shape determined from the photogrammetric analysis;

Fig. 20 shows a plot showing the relative depth coordinate deviations between the measured paraboidal data and an ideal paraboloid based on data in Fig. 19;

Fig. 21 shows a layout of flux mapping equipment and measurement components;

Fig. 22 shows a plot of variation of flux image Gaussian standard deviation as a function of mirror panel-to-target distance for the foam mirror panel flux image;

Fig. 23 shows X and Y cross sections through flux intensity distribution for foam filled mirror flux image;

Fig. 24 shows a plot of Percent-Power-In-Radius (PIR) for the flux;

Fig. 25 shows a Hot-laminated glass-on-metal-laminate (GOML) foam-core mirror panel on a mounting frame;

Fig. 26 shows a Spherical fibre-glass mould in an oven with a trapezoidal mirror facet and vacuum bag;

Fig. 27 depicts a surface plot of the triangular mirror panel of Fig. 25;

Fig. 28 shows a plot of depth deviation data for ideal surface (ROC=35.28m) subtracted from measured depth coordinates of Fig. 25;

Fig. 29 shows a frequency distribution of surface slope errors across the mirror panel of Fig. 25;

Fig. 30 shows X- and Y-cross-sections through a measured flux distribution of Fig. 25;

Fig. 31 shows a Percent power-in-radius (PIR) plot for the flux distribution of Fig. 30;

Fig. 32 depicts deflections at 3 locations on the surface of the mirror panel of Fig 25 as a function of equivalent hydraulic loading pressure;

Figs. 33A and 33B show a possible flow chart for a process for fabricating mirror panels;

Fig. 34 depicts a mirror cleaning tunnel;

Fig. 35 depicts a radiant heat oven for laminating glass-on-metal-laminate elements;

Fig. 36 depicts a heated clamshell mould for panel fabrication;

APPENDIX A sets out attributes of various skin materials;

APPENDIX B sets out attributes of various core filler materials;

APPENDIX C sets out salient qualities of a range of panel designs based on different combinations of materials and construction techniques; and

APPENDIX D shows a spread sheet calculation of the costs associated with trapezoidal sub-panels.

Detailed Description

Where reference is made in any one or more of the accompanying drawings to steps and/or features, which have the same reference numerals, those steps and/or features have for the purposes of this description the same function(s) or operation(s), unless the contrary intention appears.

It is to be noted that the discussions contained in the "Background" section and the section above relating to prior art arrangements relate to discussions of documents or devices which may form public knowledge through their respective publication and/or use. Such representations should not be interpreted as a representation by the present inventor(s) or the patent applicant that such documents or devices in any way form part of the common general knowledge in the art.

Overview Section

Concern about greenhouse gas emissions and consequent climate change is increasing. There is, as a result, growing recognition of the importance of concentrating solar power as a major source of energy. In order for concentrating solar power to play this role however, a number of requirements need to be met. One of these requirements is for light weight, cost effective, reliable solar concentrators. A critical component of such concentrators is a curved highly reflective mirror panel. Solar concentrators can be categorised as Dish systems, Trough systems, Linear Fresnell systems, Central receiver plus heliostat systems. All of the system types employed curved mirrors.

A solar mirror sandwich panel is disclosed, comprising a reflective lamina component having a reflective surface that has an average slope error of less than or equal to about 6 milliradians and preferably less than 2 milliradians, two metal skin components for stiffening the solar panel, and a core filler component disposed between the metal skin components, wherein said components are bonded together using adhesive and are arranged in a curved configuration to provide a curved solar mirror panel.

Also disclosed is a solar mirror sandwich panel, comprising a reflective lamina component having a reflective surface formed on side of said reflective lamina component, two metal skin components for stiffening the solar panel, and a core filler component disposed between the metal skin components, said core filler component being material selected from the group consisting of expanded polystyrene, paper honeycomb, fibreboard, and cardboard, wherein said components are bonded together using adhesive and are arranged in a curved configuration to provide a curved solar mirror panel.

In the solar mirror sandwich panel the core filler component may comprise at least one of a polymer, paper honeycomb, plastics, and cardboard. The reflective lamina component may comprise a glass sheet with a mirror backing. The glass sheet may have a thickness of less than about 2 mm. A thickness of said core filler component may be between about 5 millimetres and about 100 millimetres. The metal skin components may comprise a steel sheet having a thickness between about 0.2 mm and 1.0 mm. The metal skin components may comprise the same materials. The metal skin components may have the same thickness. The components may be bonded using one or more adhesives. The components may be bonded using fusible film. The components may be bonded using hot melt adhesive. The components may be bonded with a fusible film of Ethyl Vinyl

Acetate having a fusing temperature of approximately 100 Degrees C. The metal skin components may comprise a steel sheet having a thickness between about 0.2 mm and 1.0 mm and which has a corrosion protection coating based in part on a zinc and aluminium formulation. The components may be bonded using a fusible Ethyl Vinyl Acetate film having a fusing temperature of approximately 100 Degrees Centigrade.

Also disclosed is a method of making a solar mirror panel, the method comprising the steps of providing an assembly comprising a reflective lamina component having a reflective surface, two metal skin components, a core filler component located between the metal skin components, and adhesive materials disposed between said components, conforming the components to a mould having an at least partially curved surface in contact with said components, and controllably heating at least part of at least one surface of the mirror panel to heat the adhesive material disposed between the core filler component and each of the reflective lamina component and the metal skin components, without heating the bulk mass of the core filler component.

In the method, the step of controllably heating at least part of at least one surface of the mirror panel may comprise applying heat using a heated body in contact with said metal skin component to set the adhesive between said metal skin components and core filler components. The step of controllably heating at least part of at least one surface of the mirror panel may comprise applying heat using a heated body in contact with said reflective lamina component to set the adhesive between said reflective lamina and core filler components. A thickness of said core filler component may between about 5 millimetres and about 100 millimetres. A single adhesive may be used between adjacent components. Two or more adhesives may be used. The adhesive material may comprise fusible film. The adhesive material may comprise a hot melt adhesive. Said heated body may comprise a metal sheet. Said core filler component may comprise expanded polystyrene (EPS). The step of controllably heating at least part of at least one surface of the mirror panel may comprise applying heat using a radiant heat lamps directed at said reflective lamina and metal skin components to set the adhesive between said reflective lamina and skin and core filler components. The step of controllably heating at least part of at least one surface of the mirror panel may comprise applying heat using a hot oven with forced convection to transfer heat to said reflective lamina and metal skin components to set the adhesive between said reflective lamina and skin and core filler components. The rate of heating and amount of heat applied to said reflective lamina and metal skin components to set the adhesive between said reflective lamina and skin and core filler components may be optimised so that the process is completed before the core material has become hotter than its own softening point.

Fig. 2 shows an example of a process 200 for fabricating a solar panel using transient thermal bonding of EPS foam cored panels.

In a first step 201 panel components are cut to size. The process follows an arrow 202 to a step 203 in which panel components are assembled as shown in Fig 1. The core material is Expanded Polystyrene (EPS). The adhesive / bonding layers are fusible films with a fusing temperature close to or slightly in excess of the softening temperature of the EPS core. The assembly may include edge strips. The process follows an arrow 204 to a step 205 in which a decision is made as to whether to elect option 1 or option 2, these representing alternate fabricating sub-processes.

If option 1 is elected, the process follows an arrow 206 to a step 207 in which heat and pressure are rapidly applied to the top and bottom of the laid up components by means of curved heated plates. The heat is conducted through the metal and glass layers and causes the film layers to melt. The pressure applied by the plates causes the components to bond in the desired curved shape. The amount of heat which is transferred and the pressure applied are such that the EPS foam does not suffer significant shrinkage or collapse. Either the thermal mass and initial temperature of the heated plates or else the initial temperature and duration of contact of the heated plates are optimised to achieve this. The heat and pressure may however be sufficient to permanently deform the EPS into a curved shape (this is desirable at it improves the optical quality of the panel and avoids creep in the panel shape). Alternatively the EPS may be pre-formed to the desired curved shape (again using moderate heat and pressure) before being assembled with the other components. The process then follows an arrow 208 to a step 209.

Returning to the step 205, if option 2 is elected, the process follows an arrow 212 to a step 213 in which, as an alternative to application of pre-heated plates, pressure is applied using curved plates, and in a following step 215, heat is rapidly applied by some other means (e.g. by heat lamps, inductive heating, oil filled tubes etc) in order to melt the film without causing the EPS to collapse. The process may then optionally follow a dashed arrow 216 to a step 217, in which cooling is applied to the plates to avoid excess heating of the EPS, the cooling being applied by passing cooled liquid through channels in the plates. The process then follows a dashed arrow 218 to the step 209.

If the cooling step 217 is not to be performed, then the process is directed from the step 215 directly to the step 209 without performing the optional step 217.

The step 209 allows the adhesive to cure, after which the process follows an arrow 210 to a step 211 in which the fabricated panel is removed from the fabrication equipment.

The disclosed invention relates to mass produceable mirror panels (also referred to as MPMPs in this specification) suitable for solar thermal power stations comprised of large dish concentrators or other types of solar concentrators, and a die/tooling system for mirror panel mass production.

The criteria in regard to which the performance of the MPMPs may be judged may include:

- Low cost
- Accurate and stable
- Capable of high production rates
- Light weight
- Durable
- Structural rigidity

Accuracy and stability

The disclosed MPMPs show an approximate surface slope error (measure of optical accuracy) of 1 to 6.0 milliradian. The surface slope error should be less than 6.0 milliradian, and preferably less than 2.0 milliradian.

MPMP samples have been subjected to 960 hours of exposure in a temperature and humidity cycling oven, and did not display significant distortion or destruction of the component parts of the panel. At least 2 full mirror panels have been exposed to outdoor weather conditions for more than 12 months, without showing signs of degradation or distortion.

Capable of high production rates

Actual rates of production of large numbers of MPMPs will depend on the numbers of production machines established and operating at any given time. The designs disclosed are suitable for high production rates.

Light weight

The MPMPs exhibit an areal weight of approximately 13 kg m-2.

Durable

MPMP samples have withstood both 960 hours of humidity and temperature cycling, and more than 12 months exposure to the elements at a test facilities at the Australian National University. The reflective element of the panel, which utilises thin glass-on-metal-laminate (GOML) technology, demonstrates very satisfactory corrosion resistance.

Developmental stages by Milestone.

The MPMP embodiments have been developed and implemented in a staged manner that can be characterised by the following Milestones.

Milestone 1.

Preliminary work.

Milestone 2.

This involved surveying and summarising a range of possible technologies that could contribute to the development of high-accuracy, cost-effective mirror panels for large area solar concentrators. The outcomes were that a range of possible construction techniques and materials were identified and itemised. The focus settled on investigating three possible construction styles:

1. Solid-body panel having its own inherent stiffness, such that it forms both a mirror-mountable substrate and a structurally self-supporting member
2. Thin, light mirror-mountable substrate with sparse supporting ribs mounted beneath the substrate for structural rigidity
3. Thin, light mirror-mountable substrate with comparatively dense supporting framework mounted beneath the substrate for structural rigidity

A separate activity investigated and identified historically significant manufacturing techniques for mirror panels from a range of different organizations and research groups. This provided a degree of focus, and offered insights into several manufacturing techniques that had not be previously appreciated.

Milestone 3.

This undertook the process of refining the most likely options for mirror panel design and fabrication, and proposed the two most promising designs for prototype development.

The two construction types identified were:

(i) "Cored" mirror panels, whereby the GOML mirror surface formed one skin of a dual-skin construction, bonded either side of a core material having significantly greater thickness than the skins.

(ii) GOML mirror with pressed-metal support ribs.

This Milestone also described refinements to the assessment criteria for the mirror panels, particularly instituting optical accuracy requirements under load, whereby 1 mrad deflection was allowed in 40 km h-1 windspeed, and methods of assessing the relative cost of panel core and skin materials were developed whereby the areal cost as a function of flexural rigidity of the core material, became a criteria of judgement between cored panels, and areal cost as a function of tensile stiffness became a criteria of judgment between the GOML mirror construction with pressed metal support ribs.

Milestone 3 also signalled significant investment into Finite Element Modelling software and techniques to assess the mechanical performance of the different designs developed.

The two panel types proposed as a result of the Milestone were:

(i) A cored mirror panel using expanded polystyrene (EPS) foam core, with sheet-metal skins, and

(ii) A sheet-metal shell construction with folded edges and central under-ribs for shape conformance, with mirrored glass bonded onto the concave panel surface after shell construction.

Milestone 4.

Milestone 4 undertook the process of constructing prototypes of the two most promising mirror panel designs proposed in Milestone 3. These were:

(i) Folded sheet metal panels with central rib supports, with hot-laminated mirror-backed glass on its top surface, and

(ii) Dual sheet metal skin bonded either side of polystyrene foam filler, with thin glass-mirror bonded onto the concave surface of the panel.

Milestone 4 described an attempt to incorporate both of these designs into one unit, whereby trapezoidal sub-panels – which had been identified for use with sheet-metal shell designs – were fabricated as a foam core construction, and the three trapezoidal elements fastened together to form the desired triangular mirror panel.

While it was later decided that this method of construction did not constitute an optimum design for manufacturing purposes, the Milestone reported on the salient performance characteristics of this panel type, and provided fabrication experience, as well as the first composite foam-core design which was subject to environmental testing. This design was not pursued further, as it became apparent that the making of large numbers of smaller trapezoidal, foam-cored sub-panels which were subsequently mounted together did not show an economical use of materials or time, compared to laying up a full panel in a process involving fewer steps, and the panel also displayed structural deflections that were 40% higher for a given load than the foam-cored panel.

Milestone 5.

Milestone 5 reported on the results of several developments.

1. Plastic deformation experiments to create curved mould surfaces for fabricating spherical mirror panels.

2. Construction of foam-cored mirror panel prototype, using trapezoidal facets.

3. Construction of glass-on-metal-on-glass-laminate (GOMOGL) mirror panel prototype using short-isosceles facets.

4. Modelling and measurement of structural deformation due to applied loads, using FEM analysis.

5. Photogrammetric surface deformation analysis of both foam-cored and GOMOGL mirror panels.

6. Videographic focal region flux distribution analysis of both the foam-cored and GOMOGL mirror panels.

Plastically deformed mould surface

The outcomes showed that in-house deformation methods were unsuitable for creating uniformly curved mould surfaces. Significant buckling became apparent, such that the desired information on levels of over-curvature required to compensate for spring-back effects was not obtained. It became apparent that more expensive studies using full-metal pressing operations would be required to answer the uncertainties inherent in the deformation process.

Foam-cored mirror panels

A foam cored mirror panel, consisting of a GOML front skin and a thin sheet-metal rear skin bonded either side of an expanded polystyrene (EPS) core, was constructed. A wet-adhesive bonding system was used, for this prototype. The foam-cored system showed superior structural rigidity over the GOMOGL construction, but required a more complex fabrication process.

GOMOGL mirror panels

A glass-on-metal-on-glass GOMOGL mirror panel, consisting of thin glass mirror bonded on the anterior side of a sheet-metal substrate, and a thin, clear glass sheet bonded to the posterior side, was fabricated using a hot-laminating system. Although the GOMOGL panel showed lower structural rigidity, it also demonstrated a high level of resistance to thermal deformation due to the symmetric force pairs that are created either side of the sheet-metal substrate.

Structural deformation modelling and measurement

Strand 7 FEM software was used to predict the structural deformations expected for the mirror panel prototypes. Physical measurements were also undertaken to confirm the predicted deformations. Physical measurement using 150 Pa (equivalent to a 60 km hr-1 wind load) distributed load on the foam-cored panel showed deflections in the order of 1.35 mm, with corresponding surface slope errors of approximately 1 milliradian. Similar loading on the GOMOGL panel showed deformations of 1.8 mm, and corresponding slope error of approximately 1.9 milliradian.

Photogrammetric surface deformation studies of the prototype mirror panels

Close-range photogrammetry was used to assess the surface deformations across the prototype mirror panels under no-load conditions. The foam-cored mirror panel showed maximum deviations in the order of □1.0 mm from an ideal paraboloidal shape, while the GOMOGL panel showed maximum deviations in the order of □2.0 mm.

Videographic flux analysis of the focal regions of the mirror panel prototypes.

The foam-cored mirror panel showed a focal flux distribution that enabled 90% light capture in a circular aperture having 0.28 m radius. The GOMOGL mirror panel prototype showed approximately 80% capture at the same aperture radius.

Both the photogrammetric surface analysis and the focal flux analysis concurred in showing the GOMOGL panel design appeared to have a poorer optical quality than the foam cored panel design.

Milestone 6

The outcomes of the previous Milestones indicated that the foam-cored mirror panel configuration showed a number of superior characteristics over the GOMOGL design. Consequently, the foam-cored panel construction was selected for refinement and finalisation as the most competitive and promising mirror panel design arising from the project. Milestone 6 produced two significant outcomes:

1. The development of a fibreglass mould that could be used for fabricating hot-laminated GOML anterior surfaces for use with the foam-cored panel construction, and,

2. The actual fabrication of pre-curved GOML facets for use with the foam-cored mirror panel design.

A second, foam-cored mirror panel prototype was constructed using the hot-laminated GOML mirror facets, and both photogrammetric surface deformation studies and videographic flux-map studies showed the panel to perform with a similar, , performance compared to the first foam-cored mirror panel constructed using wet-bonding methods reported in regard to Milestone 5.

Milestone 7

Milestone 7 reported the results of a design study for a feasible manufacturing process for producing the foam-cored mirror panel.

Conclusions

A mirror panel design and construction process has been developed to produce a functional MPMP unit that satisfies the original design criteria. Quantitatively, these criteria have been satisfied according the following results:

1. Low cost.

Estimates using both labour, external fabrication costs and materials indicate an expected areal cost for the EPS foam-cored mirror panel of approximately $AUD120 m-2.

2. Accuracy and stability (including structural rigidity)

Overall surface slope error of 4-5 milliradian is apparent for the unloaded foam-cored mirror panel prototypes.

Loaded deflection errors of approximately 1-1.5 milliradian under a distributed load of 150 Pa (corresponding to a 40 km hr-1 wind load) apparent, which is acceptably close to the design deflection of 1.0 milliradian.

3. High production volume capability

Using suitable fabrication facilities, one production unit would be expected to produce approximately 1 mirror panel per hour. Multiple production units would scale this rate up proportionately.

4. Light weight

The foam-cored mirror panel has an areal weight of approximately 13 kg m-2.

5. Durable

Both the GOML system and the foam-cored panel system have been subject to more than 2,500 and 960 hours, respectively, of exposure in a temperature/humidity cycling chamber. These tests indicate a high resistance to temperature and moisture degradation, with no apparent destruction occurring in the units during, or after, the tests. The GOML system has also been subject to more extreme accelerated weathering tests in the BHP 'Q-Fog' salt-spray testing chamber, and has shown excellent resistance to this very aggressive environment.

Overall the panel design shows a high level of promise, and is now ready for further advances in establishing manufacturing facilities as demand for large installations of the panel technology becomes apparent.

Further details of some of the Milestones referred to above are presented below.

Milestone Details.

Milestone 1

This Milestone undertook the process of surveying and summarising a range of possible technologies that could contribute to the development of high-accuracy, cost-effective mirror panels for large area solar concentrators. The outcomes of this investigation are summarised as follows:

- A study was commissioned to research salient technologies that have been developed or utilised by previous research organisations. This study condenses a large range of knowledge that provides a sound basis for both defining the most promising research directions for mirror panel development, and streamlining the assessment of present panel designs.
- A survey of promising current technologies was undertaken to confirm the options available and to ensure that no new technology had been overlooked since the original project application.

Overall, the following possible mirror panel constructions were canvassed:

1. Solid-body panel having its own inherent stiffness, such that it forms both a mirror-mountable substrate and a structurally self-supporting member
2. Thin, light mirror-mountable substrate with sparse supporting ribs mounted beneath the substrate for structural rigidity
3. Thin, light mirror-mountable substrate with comparatively dense supporting framework mounted beneath the substrate for structural rigidity

Examples of type 1 structures are thick foam/fibreglass shell structures and the Armacel™ range of products (consisting of thick, low-density core material wrapped in vacuum heat-shrunk plastic film).

Type 2 structures use thin substrate material (eg. polymer or sheet metal) upon which a mirror can be mounted, and several (generally 3 to 6) supporting ribs beneath the substrate that provide rigidity and shape control.

Type 3 structures are similar to Type 2 devices, but use a more dense supporting structure under the substrate that constitutes a 3-D framework with multiple contact points between the substrate and the framework.

Of course, several combinations of these types could be configured, eg. Type 1 combined with Types 2 or 3, and while these have not been discounted in the present considerations, the investigations already spawned by considering these 3 types alone has generated a range of options that have consumed the time available.

Assessment of the suitability of the different panel designs has been initiated using the following criteria:

1. Ability to maintain required surface shape and optical accuracy
2. Likely cost of materials
3. Likely cost of manufacture
4. Amenability to bonding with mirrored glass – from both a manufacturing and structural integrity perspective
5. Likely weight of the finished panel
6. Susceptibility to environmental degradation
7. Amenability to mount the finished panel on an underlying subframe (ie. a dish structure)
8. Amenability to rapid production techniques
9. Thermal expansion and temperature stability of both the substrate material and the mirror/substrate combination
10. Resistance of the structure to hail impact

Outcomes to present

<u>Type 1 constructions (solid-body panels)</u>

• **Armacel products.** **Advantages:** - light weight - structurally rigid, depending on core material - rapid manufacture

- reasonable cost of materials and manufacture **Disadvantages:** - current production machinery will not handle required panel dimensions (2.2 m triangles) **Uncertainties:** - unproven long-term environmental durability to moisture ingress, UV degradation and thermal cycling - undefined method of forming core material to correct shape - unproven attainment of optical accuracy - unproven bonding integrity between mirror and substrate **Likely costs (incl. materials and production):** $55 /m^2
• **Foam-cored fibreglass panels** **Advantages:** - Proven long-term environmental stability - Good structural rigidity - Appears to offer good optical accuracy (based on experience with similar Type 3 panels used for the Israeli Big Dish) **Disadvantages:** - High costs due cost of materials and labour intensive manufacture - Comparatively slow production times - Can be high weight, depending on core-to-fibreglass component ratio **Uncertainties:** - Difficult to cost due to undefined material volumes required to achieve desired rigidity **Likely costs (incl. materials and production):** probably less than $100/m^2
• **Blow-moulded plastic panels filled with foam** **Advantages:** - reasonable cost - rapid production time **Disadvantages:** - Unable to make full-size (2.2 m) panels - Unlikely to achieve desired accuracy **Uncertainties:** - Unknown environmental degradation characteristics **Likely costs (incl. materials and production):**Information not yet returned from company

Type 2 constructions (light substrate with sparse ribs)

- **Hot-sagged glass mirrors on support frame**

Advantages:
- One-step forming operation
- Simple construction and assembly
- established technique for trough concentrators

Disadvantages:
- High cost

Uncertainties:
- unknown optical characteristics for 3-dimensionally curved surfaces (as required for dish concentrator)

Likely costs (incl. materials and production): approx. $100-$200 /m^2

- **Sheet metal substrate with folded edges and/or attached metal ribs to maintain shape**

Advantages:
- low cost
- rapid manufacture
- good environmental durability
- low weight
- promising low-cost tooling and folding operations

Disadvantages:
- separate support ribs must be constructed and attached after panel manufacture

Uncertainties
- unknown shape conformance
- undefined structural integrity (panel could be too 'floppy', depending on choice of support ribs)
- unknown if suitable sheet metal sizes can be obtained for single-panel production

Likely costs (incl. materials and production): $60 /$m^2$

- **Sheet metal substrate with folded edges and integrally folded ribs in the central regions to maintain shape**

Advantages:
- as for previous Type 2 construction, plus
- one-step stamping and folding operation

Disadvantages:
- unable to find manufacturer who can stamp and press 2.2 m triangular panels
- increased susceptibility for mirrored-glass to fracture in region of integrally folded rib due to loss of support area under the glass at the rib site.
- probable very high costs for tool & die fabrication, also requiring extremely high tonnage presses to operate

Uncertainties:
- as for previous Type 2 construction

Likely costs (incl. materials and production): $60 /$m^2$

- **Injection moulded polymer panel with either separately attached and/or integrally molded sparse ribs**

Advantages:
- Straight-forward die and mold design
- Straight-forward fabrication step
- Likely to offer low-costs

Disadvantages:
- High set-up costs (mould fabrication)

Uncertainties:
- Unknown shape conformance
- Unknown structural rigidity
- Unknown environmental degradation characteristics

Likely costs (incl. materials and production): undefined at time of writing

Type 3 constructions (light substrate with dense supporting framework)

• **Light foam-cored fibreglass substrate with light-wire mesh supporting frame** **Advantages:** - known technology (used for Israel Big Dish) - good environmental durability - good optical accuracy - good weight **Disadvantages:** - high cost - labour intensive and comparatively slow production rates **Uncertainties:** - Unclear if other production process can be developed to reduce costs and production time. **Likely costs (incl. materials and production):** $300/m^2$
• **Light substrate with Weldmesh™ support frame pressed into required shape** **Advantages:** - Uses standard commercial product for support frame - Pressing of mesh into the shape for substrate support has simpler tooling demands than tooling for full-contact sheet-metal pressing. - potential for low-cost production **Disadvantages:** - see Uncertainties **Uncertainties:** - Unknown shape conformance - Undefined bonding method(s) for fixing substrate to support frame - Unknown stamping size limitations **Likely costs (incl. materials and production):** depends on substrate costs. Weldmesh is approx. $10 /m^2$

Conclusions

A range of mirror panel construction options have been reviewed and summarised. While the original proposed option of stamped and pressed sheet-metal substrate with thin mirrored glass reflector still appears amongst the most promising technologies, the prospect of light substrates mounted onto a wire-mesh support frame has also arisen offering possible advantages as well.

Milestone 3

This Milestone undertook the process of refining the most likely options for mirror panel design and fabrication, and proposes the two most promising designs for prototype development.

In brief, the following two mirror panel constructions are put forward for further development during the course of the project:

1. A panel comprised of an expanded polystyrene (EPS) foam filler bonded between two sheet metal skins, with the entire structure formed at the time of bonding (by conformance to a mould) to take up a spherical shape, as shown in Fig. 1. The thin back-silvered glass mirror would be bonded onto the concave metal skin.

2. A panel having a pressed sheet-metal skin, with curved, folded returns pressed into its perimeter and curved, pressed-metal ribs mounted beneath the central regions of the panel.

Justification for proposed prototypes

Assessment of skin and filler materials

As discussed in Milestone 2, the 3 major styles of panel construction made use of skins and/or core filler materials. It was decided to study the available materials for cost effectiveness as a function of tensile stiffness for skins, and as a function of $E.t^2$ for filler materials (where E is Young's modulus for a material and t is its thickness – see section 0)

Skins

The following skin materials were assessed:

1. Sheet steel (Galvabond and Colorbond)
2. Sheet aluminium
3. Polyethylene (PET) plastic film
4. Luran plastic film
5. Noryl plastic film
6. Fibreglass composite (several different types)
7. Injection moulded thermoplastic

Fillers

The following filler materials were assessed:

1. Expanded polystyrene foam (EPS)
2. Extruded polystyrene foam (Styrofoam)
3. "Divinycell" high density PVC foam
4. Polyurethane foam
5. Expanded (or aerated) concrete
6. Paper honeycomb
7. Corrugated fibreboard (cardboard)

Assessment of frame/truss support structures

One of the 3 panel styles put forward in Milestone 2 incorporated a wire frame/truss substructure supporting a skin substrate. This frame substructure poses some difficulty in categorisation of performance, as many different designs could be contemplated, and an endless process of assessment could be undertaken on variations of the different designs.

It was eventually decided that two particular designs would be assessed because their structure was defined and performance/cost data was readily available for both of them. These two designs were:

1. Tetrahedral wire frame as used for mirror panel support in the 400 m2 dish constructed for Ben Gurion University in Israel;
2. Standard 'Weldmesh' wire frame, pressed to take spherical coordinates at strategic nodal positions of the mesh.

These frame structures were primarily analysed as supports to a sheet metal skin, although other combinations would also be possible. Figures for the maximum deflection under load, the mean surface slope error, and the effective cost per unit area of these designs were calculated for comparison with the filler materials.

<u>Assessment of rib support structures</u>

The final panel style considered used a sheet metal rib support structure, in conjunction with a sheet metal skin. Deflections and slope errors were calculated, and some optimisation of these parameters against areal cost was undertaken.

<u>Further assessment criteria</u>

It is apparent that simple comparisons of costs and material properties will yield limited information regarding the likely performance or amenability to fabrication of a finished mirror panel.

It is also clear that the materials can be put together in a variety of different designs and combinations, and these specific structures must be assessed as a whole for their performance and cost viability.

Also, as put forward in Milestone 2, attractiveness of a particular design or combination of materials must be judged against a large range of criteria. Specifically, these are:

11. Ability to maintain required surface shape and optical accuracy
12. Likely cost of materials
13. Likely cost of manufacture
14. Amenability to bonding with mirrored glass – from both a manufacturing and structural integrity perspective
15. Likely weight of the finished panel
16. Susceptibility to environmental degradation

17. Amenability to mount the finished panel on an underlying subframe (ie. a dish structure)
18. Amenability to rapid production techniques
19. Thermal expansion and temperature stability of both the substrate material and the mirror/substrate combination
20. Resistance of the structure to hail impact

Development of assessment criteria.

It was decided that complete structures incorporating a range of different materials and designs should be assessed for their likely cost for a given specification. Experience has indicated that an average surface slope error of between 4 and 6 milliradian is adequate to maintain optical performance levels for a dish concentrator used for solar-thermal applications. To maintain these figures to within ±1 milliradian is an adequate measure of precision to maintain accuracy, and to suffer this degree of angular deflection under a wind load of 40 km h^{-1} and a normal gravitational load was considered to be a representative loading under which tracking could still take place (a consistent 40 km h^{-1} wind would not be anticipated under clear, sunny conditions, and would be more indicative of approaching bad weather, in which case tracking and optical accuracy would be irrelevant). For the case of uniform mirror panels having approximately 2.2 m on a side, to obtain a mean structural angular deflection of 1 milliradian translates to approximately 1 mm of displacement at the centre of the panel. If however the panel exhibits local structure (as is the case where there is any form of frame or rib support, which will not be uniform over the area of the panel), then the ratio of mean slope error to maximum deflection will generally increase. In this case the mean slope error is more relevant than the structural deflection.

Using this structural deflection and mean slope error as assessment criteria has allowed finite element analysis (FEA) models to be constructed for the different mirror panel designs, such that material quantities can be calculated and likely production techniques can be costed to put forward an estimate of the overall cost per unit area for a given panel design that meets the deflection criteria. Costings were calculated assuming a production volume of approximately 43,000 mirror panels.

Assessment of panel materials and designs

Skin materials

Fig. 3 shows a plot of cost per unit area as a function of the tensile stiffness (given by the tensile modulus times thickness) for the different skin materials. Preliminary criteria for assessment of the skins was lowest areal cost for a given tensile stiffness. From the results shown in Fig. 3, it appears that sheet steel is the most cost-effective skin material, unless a skin with relatively low stiffness is required. Judged in the light of the other 9 criteria listed in section 0, sheet steel does appear to have a high probability of satisfying these as well.

Please refer to Appendix A for a fuller description of the attributes of other skin materials that also minimise their likelihood of meeting the assessment criteria.

Filler materials

A symmetric sandwich panel made up of two identical skins of thickness t_s and Young's modulus E_s and a core of thickness t_c and Young's modulus E_c has an apparent Young's modulus in flexure given by –

$$E_{flex} = E_s - (1 - 2t_s/h)^3 (E_s - E_c) \qquad (1)$$

where $h = 2\,t_s + t_c$ is the total thickness of the panel. The flexural rigidity, D, of a panel is given by –

$$D = E_{flex}\, h^3 / 12\, (1 - v^2) \qquad (2)$$

where v is Poisson's ratio. Assuming that $E_s >> E_c$ and substituting Equation 1 into Equation 2 gives the functional dependence of D on the core and skin properties as (approximately) –

$$D \propto (2t_s + t_c)^2 E_s\, t_s \qquad (3)$$

(which incidentally justifies the use of Et as the parameter of merit for skin materials). It is seen that D depends on the square of the core thickness if $t_s << t_c$ In view of this the parameter chosen to measure the 'quality' of the core was $E_c\, t_c^2$ i.e. the Young's modulus times the square of the thickness. Fig. 4 shows a plot of cost per square metre against $E_c\, t_c^2$ for a range of different foam core materials.

Examination of Fig. 4 indicates that expanded polystyrene (EPS) and extruded polystyrene (Styrofoam) are the most cost-effective filler materials for consideration – i.e. they have the lowest ratio of cost per square metre to Et^2. Paper honeycomb and cardboard are not shown on the graph but should also be considered, as they are both rigid and relatively inexpensive. However, judged by the other criteria paper honeycomb has two major drawbacks, in that it,

(i) probably has a poor environmental durability, particularly to condensates or water ingress[1], and,

(ii) it exhibits 'anticlastic' behaviour – i.e. when curved in one sense (say, concave) in one dimension, it curves oppositely (i.e. convex) in the orthogonal dimension. This effect would mitigate against maintenance of optical accuracy for any surface based on this type of structure.

Corrugated fibreboard (cardboard) also suffers from defect (i) above and is also not readily deformable to a spherical profile.

Fig. 4 shows that Styrofoam has a comparable cost / Et^2 ratio to EPS. However it is less suited to the present application as it can only be obtained in flat sheets, which must be hot wire cut or machined to the desired shape. It is also not readily available in sheets of the required width.

Please refer to Appendix B for a fuller discussion of the attributes of other filler materials and their likelihood of meeting the assessment criteria.

Frames/Trusses and Ribs

Table 1 presents the results of cost versus rigidity calculations for tetrahedral space-frame, pressed/formed 'Weldmesh' wire grid, and pressed metal ribs. These three structures are taken (for comparison purposes) as supporting a laminate made up of a 1mm thick mirror bonded to 0.8mm thick sheet steel.

[1] Although some measure of protection can be obtained by impregnating the honeycomb with a wax or resin, this would increase the cost of the material significantly.

Table 1

Structure type	Estimated cost per square metre of support structure	Mean slope error (milliradians)	Weight kg/m^2
Tetrahedral frame	$15	4.0	7.0
Pressed weldmesh	~$10 + cost of forming	5.7	5.0
Pressed sheet metal ribs	~$10 - $15	1.0	1.2

Only the pressed metal ribs provide the required degree of rigidity at an acceptable cost – increasing the rigidity of either the tetrahedral frame or the pressed weldmesh to reduce the slope error would require a significant increase in their cost and weight.

The tetrahedral frame and pressed Weldmesh supports could possibly be of interest where the main panel has an intermediate rigidity, requiring a lesser degree of support than a glass on metal laminate. Examples of this are the various fibreglass panels and an Armacel panel (see Table C.1). However the fibreglass panels are already more expensive than other options, even without the addition of a frame. In the case of an Armacel panel extra rigidity can be obtained more cheaply by increasing the core thickness than by adding a frame; and the mounting of a frame to an Armacel panel would require the bonding of the frame to the film surface at a number (~10) of points.

Panel structure designs and their assessment

Appendix C describes the salient qualities of a range of panel designs based on different combinations of materials and construction techniques. Where appropriate the structural components in the different designs were adjusted to meet the specification criteria of 1 mm deflection in the centre of the panel. Costing estimates were then made of the different aspects of the designs, i.e. materials, construction, tooling. From these estimates, an overall areal cost for the different designs was arrived at.

Table C.1 in Appendix C shows the weight, costs and structural properties of a range of panel designs. Three different designs are seen to be in the desired range:

- Armacel panel with EPS core
- Sheet steel + EPS sandwich panel
- Glass on metal laminate with pressed metal ribs

Although an Armacel panel scores well in terms of cost and weight, it is less attractive in a number of other areas:

- Durability: Armacel cannot at present be regarded as a proven material for long term (10-20 years) of outdoor use.
- Thermal properties: thermoplastic skins typically have a much higher coefficient of thermal expansion than that of glass. In the case of Luran S 797 S film the difference is so large as to result in significant distortion of a panel under the anticipated environmental temperature range. Although films of lower coefficient of thermal expansion are available, they are generally expensive.
- Relatively low tensile modulus of the skin material: this leads to a quite thick (~90 mm) EPS core being required in order to achieve the desired rigidity. Of possibly greater concern is the effect of having mirror glass, $E \cong 70$ GPa, bonded to a film with $E \cong 2$ GPa. This large difference results in the complete panel being a highly asymmetric laminate in which coupling effects will be significant, and in which any loss of continuity of the mirror surface (due to cracking or to the gaps between mirror facets) could result in severe local distortion of the panel profile.

Although the above problems may not be insuperable, in view of the apparent lack of any worthwhile cost advantage it is not proposed to further investigate Armacel as a panel material.

Choice of sheet metal skin material

Sheet steel appropriately coated for corrosion protection is the skin material that best meets the selection criteria. The coating must be compatible with the bonding methods applied including the bonding of mirror to the outer surface. Good results have been obtained using a commercial product (Colorbond) consisting of a steel sheet with a Zinc / Aluminium (Zincalume) coating under a paint coating. The sheet metal surface should not suffer from significant outgassing after bonding to the mirror.

Conclusions

Consideration of all the factors discussed above and in the appendices, has enabled us to put forward two designs for prototype production. These are:

1. Colorbond skin (0.42 mm) bonded either side of an expanded polystyrene (EPS) core. A spherical shape will be impressed on the panel front surface by producing the panels on a suitable mould. Thin (1.0 mm) mirrored glass will be bonded onto the front (concave) surface of the panel after panel manufacture.
2. Colorbond skin (0.8 mm) pressed to have folded, curved edges, with central area rib support on the underside of the panel. Thin (1.0 mm) mirrored glass will be bonded onto the front (concave) side of the panel after panel manufacture.

These two designs are showing approximately equal promise for maintaining the criteria listed in section 0, particularly low costs, high accuracy, rapid manufacture and good environmental durability.

Milestone 4

Panel design and construction considerations

This Milestone undertook the process of constructing prototypes of the two most promising mirror panel designs proposed in the last Milestone 3. These were:

(i) Folded sheet metal panels with central rib supports, with hot-laminated mirror-backed glass on its top surface, and

(ii) Dual sheet metal skin bonded either side of polystyrene foam filler.

In actual fact, both of these designs have been combined into one panel design, whereby sheet metal panels have been constructed with folded, curved edges around their periphery, and two of these (identical) panels have been bonded either side of a polystyrene filler sheet. Fig. 5 shows a cross-sectional plot through this design.

The triangular panel shape has also been modified such that it is composed of 3 sub-panels. This strategy has been dictated by the availability of commercial sheet metal coming in maximum widths of 1500 mm (a complete triangular mirror panel 2200 to 2400 mm on a side has a vertical height of 1900 to 2100 mm, also requiring extra width around its periphery for the folded edges). Three sub-panel shapes have been considered, consisting of

(i) short isosceles triangles

(ii) trapezoidal shapes

(iii) trapezium shapes

and are shown in Figs. 6, 7 and 8.

The short isosceles triangle and trapezoid sub-shapes represent approximately equal, optimal (minimum wastage) use of sheet metal, while the trapezium shape, due to its non-parallel edge nature, does not make optimum use of sheet metal area, and was thus discarded from further consideration.

FEM modelling was used to study the likely structural deflections for the short isosceles and trapezoidal sub-shapes under an equivalent wind load of 40 km hr^{-1}, for both single, folded sheet metal (0.8 mm) shells, and for dual-skin sheet metal (2 x 0.35 mm) bonded either side of a foam filler. Table 1 shows the predicted deflections from this analysis.

Table 1. Predicted deflections for short isosceles and trapezoidal sub-panel shapes assembled into 2.2 m triangular panels.

Sub-panel shape	Metal shell (0.8 mm) (Vertical deflection/slope error)*	Dual skin (0.35 mm), foam core (Vertical deflection/slope error)*
Short isosceles	0.9 mm/1.8 mrad	~0.4 mm/<1.0 mrad**
Trapezoid	2.4 mm/5.4 mrad	~1.0 mm/<1.0 mrad**

*The vertical deflection/slope error figures are averaged across the surface of an assembled triangular panel comprised of 3 sub-panels.

**It should be noted that the predicted deflections for a 'solid' panel using a foam core have larger error bands than those applicable to simple glass-on-metal-laminate metal shell designs due to an inherent modelling limitation in Strand7 (FEM program) that prohibits calculation of shear deformations within highly compressible filler materials (such as EPS foam). Calculations are performed as if the filler material was incompressible, and then correction factors are applied for shear deformation, subject to the particular geometry of the panel shape, which allow an approximate prediction of the surface deformations.

The results in Table 2 indicate that a trapezoidal shape would be unacceptable as a metal shell, but would perform acceptably as a dual metal skin, foam core construction. The short isosceles triangle appears to offer 'borderline' performance as a shell, but quite acceptable performance as a dual skin foam core construction.

Panel fabrication

Based on these results, consideration was given to investigate stamping and pressing requirements for the short isosceles panel shape. Discussions have been pursued to construct a polymer composite die and tool set that will press metal panel shapes. One limitation that has been encountered which rules out the short isosceles triangle sub-panel shape, leaving the trapezoidal shape, and its associated construction requirements of dual skin, foam core as the sub-panel shape to be built as a prototype.

Hand-made prototypes have been constructed to assess the likely performance that can be expected from this sub-panel shape. Fig. 10 shows one of the two trapezoidal sub-panels. The trapezoidal sub-panel was fabricated using two 0.35 mm colorbond skins with curved, folded edge returns, bonded either side of a 30 mm thick expanded polystyrene (EPS) sheet, as shown schematically in Fig. 5. The mirrored glass was bonded onto the sub-panel while pressed between the metal/foam panel and a spherical mould surface, such that the glass/front surface of the panel continued to hold the spherical shape after the adhesive had set and the sub-panel was removed from the mould.

Performance assessment

Structural deformation

Structural deflection tests were performed on square, dual skin, foam core test panel, having dimensions 1.2 m x 1.2 m x 30 mm (EPS thickness) x 2x0.35 mm (colorbond sheets), by supporting it at its four vertices, applying a distributed load (water bags) over a 1 m x 1 m central area, and measuring the deflection at its centroid. Fig. 9 shows the results of these deflection tests.

A hydraulic pressure loading of 150 Pa corresponds to an equivalent wind speed of 40 km hr^{-1}. Fig. 9 indicates that a deflection between approximately 0.5 mm and 0.9 mm occurs at this loading. These deflection figures indicate a slope error of between 0.8 milliradian and 1.5 milliradian. These figures are considered to be acceptably close to the design slope error of 1.0 milliradian, and also show a good agreement with the model-generated predictions in Table 2.

Optical performance

The mirror sub-panel focal distribution was tested in a preliminary manner by pointing it at the sun and focusing its focal region onto a white screen. Focal area minimisation appeared to occur at a distance of approximately 14 m to 16 m from the sub-panel,.

Fig. 11 shows a contour plot of a flux distribution, and a crude analysis indicates that an estimated 90% of the flux distribution falls within an approximate diameter of 500 mm. By way of comparison, the ANU 400 m^2 Dish receiver has an entrance aperture diameter of 700 mm, and if similar sub-panels as the present hand-made unit were used to cover the surface of the dish, it could be anticipated that 100% of the reflected flux would be captured, as compared to less than 85% with the existing mirror panels.

Panel production costs.

Appendix D shows a spread sheet calculation of the costs of component materials and operations deemed necessary to undertake a production run of trapezoidal sub-panels sufficient to provide the reflecting surfaces for 200 x 400 m^2 solar concentrators. These calculations indicate that the overall areal cost for the dual metal skin, foam core with curved, folded edges can be anticipated to be in the order of $AUD135 m^{-2}. This shows a favourable comparison with other reflector technologies, and gives the authors a great deal of encouragement to finalise the sub-panel design components and undertake further prototype manufacture using high accuracy metal pressing operations.

Conclusions

The deflection tests show acceptable levels of slope error for the dual skin, foam core panel construction. Hand fabrication of a trapezoidal sub-panel has shown that folded, curved edges on a metal panel are achievable, and that the curved shape propagates into the sub-panel surface. Focal flux assessments have indicated a very encouraging optical performance from the prototype sub-panel, and costings obtained for sheet metal pressing operations are indicating that at least a demonstration panel fabrication system using commercial metal pressing operations should be achievable within the present project.

Milestone 5

Milestone 4 detailed the design, construction and preliminary performance characteristics of a prototype trapezoidal, foam-filled mirror sub-panel. That stage of the project combined the two panel designs put forward in Milestone 3, into one panel. Work has progressed further under the present Milestone to produce working, full-size prototypes of two panels, with the introduction of a new glass-on-metal-laminate (GOML) design that has been designated GOMOGL – glass-on-metal-on-glass-laminate. The two panels are thus constructed as:

(i) the foam-filled, metal skin, and

(ii) GOMOGL only, with no interior fill material.

The stated objective for the present Milestone was that the 'Design(s) be revised, and the final prototype should be complete'. This overall objective was broken down into four major sub-objectives:

(i) Determination of the correct degree of plastic deformation that should be applied to the metal substrates used for laminate production, such that optimal radii of curvature could be specified for a metal-pressing operation that would manufacture the panel substrates.

(ii) Fabrication of working prototypes of the two panel designs.

(iii) Structural and optical performance testing of the panels.

(iv) Specification of the most effective panel design that optimises panel cost, manufacturability, optical accuracy and areal mass.

Investigation of sub-objective (i) – plastic deformation of metal substrates

One of the intended goals of the present Milestone was to deliver a specification to a metal pressing company for the correct curvature and profile required for the sheet-metal substrate to be moulded and correctly form a hot-laminated GOML panel as a final product. The determination of the correct precurvature for the substrates is an essential parameter that compensates for both the natural spring-back of the laminate when it is released from the laminating oven, and for the differential contraction rates that occur between the glass and metal components as they cool down to ambient temperatures after lamination. To this end, several techniques and experiments were undertaken to quantify the spring-back and differential contraction effects.

Finite element analysis (FEA) modelling with Strand 7.

FEA models of curved shell elements were created and analysed using Strand 7 software, and the deformation of these models under both spring-back and differential expansion conditions were assessed. Software modelling of spring-back effects in plastically deformed shells cannot however be relied upon to produce results with the accuracy required. It became clear that an experimental assessment of plastically deformed shells should be undertaken.

Construction of an in-house metal forming mould

Efforts were then directed to the construction of a heavy metal-frame mould, having a short isosceles triangle (SIT) aperture that could be used to apply curved, folded edges to the perimeter of sheet-metal substrates, with the intent of measuring the degree of deflection that occurred in substrates made with the mould after they were laminated with glass in the laminating oven.

However, it also became apparent that such a design would have limited comparison with a fully plastically deformed metal substrate, such as would be made from a metal pressing operation, because the concept of applying curved, folded edges to a sub-panel still left the central regions of the panel in a state of residual stress, trying to return to its original flat state.

An experiment was then devised that used the heavy metal-frame mould to clamp two sheets of metal together at the edges, with a sealing strip clamped between them, and then apply a hydrostatic pressure to the cavity between the sheets, such that they were forced to 'bubble apart', and thus form a plastically deformed, curved metal shell. This would then be used for hot laminating with glass and deflection tests undertaken.

It became apparent that highly inhomogeneous deformations, in the form of creases were occurring at the three corner regions of the SIT panels, such that the surfaces were not smoothly deformed, but they instead became totally unsuitable for laminating with glass.

It was noted that the folded edges of the sub-panel had been pulled in substantially during the deformation process, and it was surmised that this flange-creep may have contributed to the interior creasing at the vertices. To test this idea, another sub-panel was constructed with 10x10 mm square steel rod welded around the perimeter of the sub-panel, and in contact with the edges of the mould so that the exterior flange/border metal could not be pulled in under the mould. Hydrostatic pressure was again applied to this arrangement, but the resulting sub-panel showed vertex creasing of a similar order to that seen with the first sub-panel.

These experiments showed that making a smooth, curved shell using hydrostatic pressure applied to the unconstrained surfaces of a metal sheet was an extremely difficult, if not impossible task. This also terminated our plans for quantifying the corrections and constraints required for pressed metal shells to overcome fabrication deformations.

Investigation of sub-objective (ii) – fabrication of working prototypes of two panel prototypes.

In light of the difficulties experienced with sub-objective (i), it was considered that it was still essential to ensure that the other basic design and fabrication concepts developed for the two panel types (i.e. foam-filled and GOML only) should be proven for full-size panels. The primary issues to be addressed were:

(i) Proof of fabrication techniques proposed for the two panel types. While the hot laminating bonding method has shown itself to be the premium method of choice for creating the glass-metal bonds, several options are available for bonding the foam core to the metal skins for the foam-filled panel type. These options have not been fully tested at the time of writing. For the present prototype, a two-part epoxy resin system was used to bond the foam core to the metal skins. It is not anticipated that this will be the final method of choice, due to the manufacturing restrictions introduced by the typically long curing times.

(ii) Measurement of structural deflection characteristics of the two panel types

(iii) Optical performance of the two panel types should be compared. While it is recognised that these optical measurements and comparisons are of limited value, as they are not performed on panels fabricated with the desired precurve built into them (using plastically deformed shells), it is important

that the optical effect of other characteristics of the panels (determined by their basic construction) should be ascertained.

To this end, two full-size panels were designed. Both of these panels have been fabricated using techniques that are advanced developments upon those described in Milestone 4.

Foam–filled mirror panel

Milestone 4 reported on the fabrication of a prototype trapezoidal foam-filled sub-panel, which used elastically deformed metal skins to acquire the desired shape. This work has been taken further, and a full-size (2 m on a side) equilateral triangular panel has been constructed, using an expanded polystyrene (EPS) foam core 38 mm thick. The structure of the present panel differs significantly from the earlier prototype. Fig. 12 shows the overall layout of the panel, while Fig. 13 shows a cross-section (not to scale) through the main structural elements of the panel. Note that while Fig. 13 appears to show a flat profile across the panel, in actual fact the panel is curved to a spherical profile having an approximate radius of curvature of 28 m.

The two previous figures show that the present foam-filled panel consists of three trapezoidal glass mirrors bonded onto three similar trapezoidal sheet metal substrates on the anterior face, which in turn are bonded onto a foam core, with a final posterior metal skin bonded to the foam. Features of this design are:

- The anterior trapezoidal sheet metal substrates are butted together at the trapezoid joints to form a completely flat surface onto which the mirror trapezoids can be bonded. This means that the panel is truly contiguous across the trapezoids, with no separation and consequential fixing between trapezoidal sub-panels.
- The sheet-metal substrate butt-joints are held together by metal lap-joint strips, bonded with epoxy adhesive on the internal (foam core) side of the metal sheets.
- The mirror trapezoids and front sheet-metal substrate trapezoids are aligned in-phase, so that the mirrors do not bridge across the substrate joints, but the rear metal trapezoidal skin are aligned out-of-phase with the joins on the front faces. This may assist cross-sub-panel rigidity. Out-of-phase layering of the front glass and metal skin will also be tested, and is attractive in that it further enhances the

cross-sub-panel rigidity. However, this design also means that the glass is providing some component of the overall structural rigidity of the overall panel. This may have adverse ramifications on rigidity if fractures in the glass along the underlying substrate butt-joints occur.

- The folded edges around the perimeter of the panel are comparatively small, having a 12mm depth. This feature has allowed the dual advantages to be achieved that (i) the folds can be applied to the sheet-metal with a normal, straight-edge metal folder, but (ii) the fold depth is such that it is large enough to provide significant edge rigidity, but is small enough to let the edges be elastically deformed to a curved profile upon fabrication. While this design has allowed successful fabrication of the panel, it does incur some residual stress in both the metal edges and the foam core, as these are stressed against their natural shapes.
- The prototype shows a number of improvements compared to the foam-filled-panel constructed for Milestone 4, which consisted of three individually fabricated segments which were subsequently joined together. The design is more rigid, has an increased glass area (due to the smaller margins between trapezoidal mirror segments), is quicker to manufacture, and does not require curves on deep folded edges

Figs. 14, 15 and 16 show front, back and side views of the foam-filled mirror panel, respectively.

Glass-On-Metal-On-Glass-Laminate (GOMOGL)

The glass-on-metal-on-glass-laminate (GOMOGL) consists of a panel of sheet-metal, bonded on either side with a sheet of glass (actually one side is mirrored glass, while the other is clear glass, to minimise cost - mirrored glass is almost twice as expensive as clear glass).

A GOMOGL SIT sub-panels may be constructed by first laying the mirror segments, then the flat sheet-metal substrate (with 12 mm straight-folded edges) then the anterior clear glass segments onto a convex (male) mould. Two part epoxy can be used to bond the layers, with compression applied using a vacuum bag to constrain the layers to take the shape of the mould while the epoxy cured. The full-size panel can be completed by fixing the GOMOGL SITs to profile-cut ribs using screws. In a production situation, an automated fastening system can replace the screws.

Structural and optical performance testing of the mirror panels

Foam filled panel – structural testing

Fig. 17 shows the surface deflections predicted by Strand 7 for the foam-filled mirror panel subject to a uniform normal load of 150 Pa. The model has the same constraints as the test conditions for the prototype panel – i.e. the bottom of the corner brackets are only fixed in the direction normal to the plane of the panel. The average (vertical) deflection is 0.31 mm and the average surface slope error is 0.29 milliradian. The figure indicates that a deflection of 0.40 mm can be expected at the centre of the panel, while a deflection of 0.37 mm can be expected at the centre of one of the trapezoidal sub-panels.

These predicted deflections, together with the measured deflections for the foam-filled panel are summarised in Table 3.

Table 3. Predicted and measured deflections for the 2.0m sided foam-filled mirror panel with corner brackets vertically fixed.

Deflection	Predicted (bending deflection only)	Measured (shear + bending deflections)
Panel centroid	0.40 mm	1.35 mm
Trapezoid sub-panel centroid	0.37 mm	1.22 mm
Average panel	0.31 mm	-
Average slope error	0.29 mrad	-

The large differences between the measured and predicted deflections are believed to mainly be due to the inability of Strand 7 to model shear deformation within a highly compressible material (i.e. the EPS core). In most situations this is not significant, but with a steel plus foam sandwich panel the deflection due to shear deformation of the core may well be larger than the pure bending deflection. If the difference between the predicted and measured deflections is due to the presence of shear deflection, then the shear deflection in the centroid of the panel must be 1.35 – 0.40 = 0.95mm.

The actual slope error, due to both shear and bending, can be estimated by scaling by the ratio of the measured total deflection to the predicted bending deflection. It then becomes 0.29 x 1.35 / 0.40 = 0.98mrad, close to the desired value of 1 mrad.

GOMOGL panel – structural testing

Table 4 summarises the relevant deflection data for the panel

Table 4. Predicted and measured deflections for the 2.0m sided GOMOGL mirror panel with corner brackets vertically fixed.

Deflection	Predicted	Measured
Panel centroid	1.16 mm	1.7 mm
SIT sub-panel centroid	1.20 mm	1.8 mm
Average panel	1.05 mm	-
Average slope error	1.34 mrad	-

The measured and predicted deflection values in Table 4 show a better correlation than that observed for the foam-filled panel. This arises because there is no compressible core material (EPS) in this structure.

A Strand 7 model of a 2.2m sided panel under dish conditions of x, y, and z fixed, predicts a maximum deflection of 0.69 mm and an average slope error of 1.27 mrad. If these are scaled by the measured / predicted deflection ratio of 1.8 / 1.2 shown in Table 4, then an expected average slope error of 1.9 mrad is obtained. This is still significantly higher than the desired figure of 1 mr under a 150 Pa load.

Foam filled mirror panel – optical performance testing

Foam filled mirror panel – photogrammetric surface analysis

A photogrammetric study was undertaken for both panel types. Photogrammetry is the technique of extracting 3-dimensional object coordinates for signalised, or unique, data points placed across the object surface. The technique uses image data from many photographs (24 photos were used in the present photogrammetric study) taken from many different viewing positions around the object to be measured. High coordinate precisions are possible with this analysis technique (relative precisions of 1: 80,000 were achieved in the present study). For the panel dimensions encountered in this study (i.e. approximately 2.2 m), absolute data point coordinate precisions of approximately 10-15 micron were obtained. This makes possible surface characterisations that highlight features that influence the optical performance of a surface.

In this particular study, approximately 1200 data points were measured across the foam-filled panel. Fig. 18 shows a layout plot of the data points arrayed across the triangular aperture of the panel, while Fig. 19 shows a contour plot of the 3D data extracted from the photogrammetric analysis of the foam-filled panel.

The plot shows a subtraction of the ideal depth coordinates from the measured depth coordinates for approximately 1200 data points across the panel surface. The ideal surface against which the measured data points are compared is a spherical surface having a 28 m radius of curvature (ROC), or 14 m focal length. This surface corresponds to the ROC of the mould on which the panel was made. It should be noted that if the measured data conformed exactly to an ideal surface, then the subtraction between the measured and ideal coordinates should leave a surface plot that is flat through the origin in the x-y plane – i.e. all deviations are zero.
The panel surface is significantly 'flatter' than the mould (i.e. the overall deviation is negative, which indicates that the panel depth coordinates are less (lower) than the mould coordinates. This is illustrated in Fig. 20 below.

This apparent 'flattening' of the panel away from the mould is entirely commensurate with typical experience with these panels, and intuition also predicts that a panel constructed of initially flat components that have been subsequently stressed to a curved profile, will always try and 'spring-back' to their initially flat shape, and will take a profile with a longer ROC than the mould.

A least-squares optimisation of the photogrammetrically measured foam-filled panel coordinates predicts that the panel should exhibit an equivalent focal length of 17.13m (or ROC = 34.26m). For photogrammetric data compared with an ideal paraboloidal surface having an optimal focal length (17.13 m) deviations fall approximately symmetrically around the zero plane. There are some significant deviations from the 34.2 m ideal surface, particularly at two vertices of the triangular panel. It is unclear at this stage whether these deviations are reflections of aberrations in the mould, or are the result of inhomogeneous fabrication processes. Further photogrammetric characterisations of the mould surface will be undertaken in order to answer this question.

Foam filled mirror panel – photographic flux mapping

Flux map procedure and analysis techniques

Flux mapping has been used to characterise the actual focal region light distributions for the mirror panels. This technique involves reflecting light from the sun from the mirror panel onto a diffuse, white target, and photographing the resulting flux distribution on the target. Fig. 21 illustrates this process.

Ideally, for the most accurate measurement of the flux distribution, the mirror panel-flux target vector should be paraxial with the mirror panel-sun vector. The layout shown in Fig. 21 shows a non-paraxial alignment. This arose because no facilities are available to mount the mirror panel and flux target at the large focal distances required from each other (approximately 13 – 20 m) and have them track the sun with a fixed alignment. The non-paraxial alignment means that the flux image captured in the present study will show some skewing, or coma. However, compared to the spread incurred in the flux distribution from the surface errors of the panels, these effects are small enough to still allow representative assessments of the focal light distributions, and put a 'worst-case' bound on the data extracted from the flux maps.

Post processing of the flux image yields information about the energy content, spatial distribution and radiant intensities of the focal spot. However, in the present set of measurements, absolute insolation measurements were not available at the time of the flux maps. Absolute values of integrated power, peak intensity and percent power within radius thus cannot be presented for the measured flux maps. However, an intrinsic calibration procedure was applied to some flux maps that displayed appropriate characteristics amenable to this procedure, and this leads to flux map parameters that will be within approximately 15% to 20% of their true values. These calibrations can be applied to all the flux images, which allows relative comparisons to be made between the flux images, although variations in insolation value between measurements will introduce the uncertainties stated previously.

In the flux map analyses, several important pieces of data are extracted. These are:

1. A determination of the optimal focal point of the mirror panels. This is achieved by fitting a 2-dimensional gaussian distribution to the flux images (taken at different panel-to-target distances), and extracting the standard deviation (SD) of the fitted distribution. Plotting this value against the panel-to-target distances shows where the SD is a minimum, which in turn defines the 'tightest' flux distribution, and the focal point for the mirror panel.
2. A determination of the peak intensity expected for the flux distribution at the optimal focal position.
3. A determination of the variation of power captured as a function of the radius from the flux distribution centroid. This allows determination of expected power capture within a receiver having a given aperture.

Flux analysis for the foam-filled mirror panel

Fig. 23 indicates that under insolation conditions of 1000 W m^{-2} a peak flux intensity of approximately 1.6×10^4 W m^{-2}, or a concentration ratio of 16 suns, can be expected. The expected peak concentration ratio for 216 such mirror panels (constituting the 400 m^2 surface area of the Generation I ANU Big Dish design) is then approximately 3,460 suns. For comparison purposes, it can be noted that the existing mirror surfaces on the ANU Dish produced a peak concentration ratio of approximately 1,200 suns when first installed. This indicates that the foam-filled mirror panel has a surface quality approximately 3 times better than the current mirror panels.

The percent-power-in-radius (PIR) plot shown in Fig. 24 indicates that 90% of the flux power would be captured within a 0.29 m radius from the flux centroid. The receiver on the ANU Dish has an aperture with a 0.35 m radius. Fig. 24 indicates that approximately 97% of the incident flux radiation would be captured in this aperture.

Specification of most effective panel design and conclusions

In terms of fabrication and amenability to manufacture, the following observations can be made for the two panel designs:

Foam-filled mirror panel

Advantages

- Lower areal mass (11 kg m^{-2})
- Allows construction of a contiguous front metal skin upon which mirrored glass can be bonded to form a high fill-factor reflector (i.e. most of the panel area is covered by mirror).
- Allows creation of mirror panels of almost any size or shape. Structural rigidity can be maintained simply by using suitable thickness foam core material.
- Is amenable to take advantage of the GOMOGL characteristics. This would use GOMOGL for the front skin, foam core bonded to this skin, and a sheet metal skin bonded onto the rear of the foam core. The extra sheet of glass in the GOMOGL configuration would, however, increase the areal mass somewhat (~3 kg m^{-2}).

GOMOGL panel

Advantages

- Offers a one-step fabrication operation – lay-up components, clamp together and bond in laminating oven.
- Has proven external environmental endurance performance

Disadvantages

- Has a higher areal mass (13.7 kg m^{-2})
- For adequate accuracy, requires plastic forming of the sheet-metal substrates to the desired curvature prior to lamination.
- Panel sizes and shapes are limited to the short-isosceles-triangle (SIT) sub-panel shape and dimensions. This cannot be extended beyond 2.2 m on its longest side before structural rigidity becomes compromised. It can be noted that even with a

2.2 m side dimension the GOMOGL panel is significantly less rigid than the foam filled panel.

- The need for folded edges at the perimeter of the SIT sub-panels introduces edge-effects that diminish the optical quality of the sub-panel.

Conclusions

Work to date has refined the two most promising mirror panel designs proposed in previous Milestones to a stage where a prototype of each panel has been constructed and their optical and structural performance characteristics have been quantified. Both panels exhibit acceptable optical performance, with the foam-filled mirror panel showing superior optical and structural rigidity performance over the GOMOGL mirror panel design.

The team's assessment of the relative merits of the two panel types is that the foam-filled mirror panel offers more attractive characteristics than those of the GOMOGL panel. Dominant of these are the ability to make large area mirror panels (significantly larger than the 2.2 m equilateral triangular panel prototype), having almost any desired aperture shape and 'tailored' structural rigidity (by the use of suitable thickness foam core material).

While the GOMOGL panel is attractive for its potentially simpler fabrication process, and its better-defined environmental durability, the need for the comparatively small SIT geometry, with folded edges on all sides of the SIT sub-panels – and their associated loss of optical performance – makes this panel less attractive than the foam-filled panel.

A closing conclusion that arises from the work achieved during the present Milestone, is that whichever construction design is pursued (either foam-filled or GOMOGL only panels), we have shown that it is not necessary to utilise or create plastically deformed sheet-metal substrates. This represents a significant saving in cost and manufacturing effort, as the extremely expensive and time-consuming process of developing metal pressing tools is now not required.

Milestone 6

The previous Milestone 5 detailed the design, construction and preliminary performance characteristics of two prototype triangular, mirror panels – the 'Foam Filled Panel' and the 'GOMOGL Panel'. In accordance with the recommendations of Milestone 5, work has progressed further under the present Milestone to:

1. Focus on, and refine, the development of the foam-cored mirror panel, and
2. Finalise the fabrication steps needed to create a hot-laminated glass-on-metal-laminate (GOML) foam-cored mirror panel

Part of the finalisation process in step 2 has been the development and fabrication of a suitable mould for fabricating hot-laminated GOML mirror panels.

The specified objective for Milestone 6 was to 'complete the performance tests'.

Outcomes

Panel production

Fig. 25 shows the hot-laminated GOML foam-core mirror panel. The panel is shown mounted on a triangular support frame.

The three trapezoidal mirror facets were fabricated on a new spherical fibreglass mould, that allowed suitable precurvatures to be impressed onto the facets before bonding to the foam core and metal backing sheet. Fig. 26 shows the fibreglass mould mounted in the bonding oven, with a trapezoidal mirror panel shown under a vacuum bag prior to lamination.

Shape conformance assessments

Ideally, for a reflector element designed for the ANU Big Dish, the fabricated mirror panel should conform to a spherical profile having a radius of curvature (ROC) of 30 m. Due to the ready availability of an existing mould with a radius of curvature of 28 m, this was used to fabricate mirror panels for this project.

Deviations of the actual fabricated mirror panel from both this ideal (28 m ROC) shape, and the closest least-squares approximated spherical surface (ROC=35.28 m) surface, have been assessed using close-range photogrammetry. Both the depth-coordinate deviations and surface slope errors across the panel have been calculated, and a ray-trace model constructed which predicts the focal region performance of the panel.

Fig. 27 shows the measured surface of the mirror panel. The panel has been oriented to fall on a regular coordinate system (x,y transverse displacements, z-depth displacement, origin at central vertex of the panel).

A subtraction of the ideal z-coordinates, for a paraboloid having a 14 m focal length, from the measured z-coordinates yields a difference surface.

This results in a mostly negative deviation between the measured and ideal surfaces. This indicates that the mirror panel surface is flatter than the mould on which it was made. This is a regular phenomenon, as the internal stresses in the panel will create a force that 'opens up', or flattens-out the panel. This effect is counteracted by fabricating the panel on a mould that has a slightly shorter radius of curvature than that desired in the final panel.

Performing a least-squares linear fit on the measured depth (z) coordinates versus their radial displacement from the origin allows an estimation of the optimal focal length for the panel. Performing this analysis yields a best-fit ROC of 35.28 m. To assess the finer detail of the panel surface deviations, a depth subtraction between the measured and ideal z-coordinates for a sphere having this best-fit ROC (35.28 m) is undertaken. Positive deviations on the surface indicate displacements of the measured surface above the ideal surface.

To assess the range of deviations evidenced across the panel, Fig. 28 shows a plot of depth-deviations versus x-displacement. The figure indicates that worst case deviations are in the order of +1mm to –2.5mm.

The panel shows positive deviations at its centre and negative deviations around its perimeter, with high positive deviations at two of its vertices. Fig. 12 of Milestone 5 shows a similar surface deviation plot for the previous foam-cored mirror panel (bonded together with wet adhesive). That is, it appears a common distortion mode for panels of this type to deflect upwards in their centres and at their vertices. However, the magnitude of deviations on the previous, wet-bonded, panel appear to be lower (approximately ± 1 mm) than those exhibited in the present (hot-laminated GOML) panel.

Ray trace flux distribution analysis.

An interpolating surface was fitted to the numerical data coordinates obtained from the photogrammetric analysis. Surface normal data was calculated from this surface, and ray-tracing undertaken to predict the shape and extent of the flux distribution that could be expected from the panel.

Fig. 29 shows the frequency distribution of surface slope errors calculated for the panel.

The mode of the distribution indicates the standard deviation of the equivalent bi-variate Gaussian distribution of slope errors for the panel. The figure indicates a primary mode of approximately 3.5 milliradian, although a secondary mode is also indicated at approximately 6.5 milliradian. This type of bi-modal distribution makes it difficult to characterise a surface with a single figure of merit (ie. slope error standard deviation), and it is clear that a simple bi-variate Gaussian distribution of surface slope errors is not a very applicable model with which to identify this surface.

Peak concentrations in the order of 12,000 to 14,000 W m^{-2} (12-14 suns) can be expected from the panel. For mirror reflectivities in the order of 90% (a realistic value), peak concentrations in the order of 10 to 12 suns could be expected. Interpretation of the performance of the focal flux distribution is best undertaken using a percent power-in-radius (PIR) plot of the power distribution in the flux region.

It has been determined that 90% of the flux power would be captured in an aperture diameter of 0.712 m. This is a 20% increase above the figure of approximately 0.6 m for the wet-laminated foam panel of Milestone 5. This leads to the conclusion that the shape conformance of the hot-laminated GOML panels is somewhat worse than that of the wet-laminated panels. However, on an absolute scale, the performance of the hot-laminated GOML panels is such that almost 90% of the reflected radiation would be captured by the 0.7m diameter receiver on the existing Big Dish at the ANU. This is satisfactory performance for this type of collector.

Videographic flux image analysis

An experimental assessment of the focal flux performance was made using videographic flux analysis, a technique described previously in Milestone 5. A 0.9 x 0.9 m target was placed at a distance of 18 m from the panel, and a flux image was projected onto the target. Fig. 30 shows x- and y-cross-sections through the resulting distribution. The sun was at approximately 40° elevation at the time of image capture, which creates an angle of incidence and reflection of 20° between the panel, the sun and the target.

Comparison of the ray-traced and measured flux distributions appears to show a different distribution of radiation between the two images, even though they display very similar radial power capture characteristics. This is partly a result of the difference in orientation of the two panels. Non-paraxial incidence will create a slightly distorted flux image from that expected for paraxial incidence.

Fig. 30 shows that the flux image saturated the camera CCD array slightly, such that the peak of the distribution is slightly truncated. Taking this into account, indicates that a peak intensity of some 10,000 W m^{-2} occurred in the distribution. This is comparable to the figure of 10,000 to 12,000 W m^{-2} predicted in the ray-trace model for the panel.

Fig. 31 shows a PIR plot for the distribution. Slight extrapolation from the graph indicates a 90% capture radius of 0.36 m. This figure also shows a good correlation with the figure of 0.356 m predicted in the ray-trace study.

Structural deflections

Fig. 32 shows the results of structural deflection tests that have been performed on the panel. The panel (Fig. 25) was loaded uniformly across its surface to simulate wind loads up to 40 km hr^{-1} (equivalent hydraulic loading of 150 Pa).

As can be seen in the figure above, deflections of approximately 1.5 mm were observed at the three test positions. This compares favourably with the same figure of 1.5 mm for the previous foam-cored mirror panel (reported in Milestone 5).

Conclusions

The prototype hot-laminated GOML mirror panel is showing acceptable performance for use in high-level concentration (approximately 500-1000 suns peak concentration ratio) applications on large-area devices such as the ANU Big Dish. Somewhat better performance appears possible using wet-laminated fabrication techniques, although this is not a preferred method of construction.

The fabrication techniques employed to produce the hot laminated GOML mirror in this report show themselves amenable to large-scale manufacturing processes.

Milestone 7

The previous Milestone 6 described the assembly and performance testing of the final prototype foam-cored mirror panel.

The specified objective for Milestone 7 was to 'Design machinery for manufacture of mirror panels'.

Outcomes

The culmination of the mirror panel development to date has been the specification of a hot-laminated glass-on-metal-laminate (GOML) front skin, bonded using adhesive to an expanded polystyrene (EPS) cored, with a sheet-metal skin bonded onto the rear side of the EPS core to produce a multi-layer sandwich structure that is optically accurate, low-weight, uses readily available component materials, structurally robust and low cost. Reference to the previous Milestone reports reveals the details of the developmental processes that were followed to reach this final design specification.

In order to fabricate machinery that will allow production of the specified mirror panels, the relevant panel assembly steps must be identified. Figs. 33A and 33B show a flow-chart of the salient components and steps that must be processed in order to produce a finished panel.

Figs. 33A and 33B show that there are six main components utilised in the mirror panel manufacture process:

1. Sheet-metal for substrates and backing skins
2. Back-silvered glass sheet
3. Expanded polystyrene (EPS) foam (or other) core material
4. Metal edge strips
5. Fusible film
6. Adhesive (or further fusible film)

The following issues with each of these components must be addressed before assembly into the finished product:

1. **Sheet-metal substrates**
   These will be supplied cut and folded (where required) to the necessary sizes and shapes. They will possibly come with a light, protective plastic film applied to one side of the sheets, which requires removal before using the sheet-metal.
2. **Back-silvered glass sheet**
   The thin glass mirrors will also be supplied cut to the required sizes and shapes. The glass typically comes with light paper between the glass sheets, and a form of talc powder is resident on the painted rear surfaces of the glass. This powder must be thoroughly removed before using the glass.
3. **Expanded polystyrene foam core material.**
   The EPS will come supplied as a flat sheet, cut to the required size and shape. No further processing is required for this component.
4. **Metal edge strips**, approximately 35mm wide, may be used for protecting the edges of the mirror panel, and for structural support, will come supplied from the manufacturer with both edges pre-cut to the required curved profile that

accommodates the curvature on the panel. These sheet-metal components also typically come with a plastic protective film that requires removal before making use of the edge strips.

5. **The fusible film** will be supplied on a roll, and must be cut to the required size and shape when laid-up between the sheet-metal substrate and the thin mirror.
6. **The wet adhesive** which may be used to bond the metal skins either side of the EPS core typically comes in drums, and must be applied, most likely with an industrial spray application system.

The most salient pieces of equipment that may be designed and fabricated to enable the mirror panel assembly process are:

1. Mirror cleaning tunnels to clean the powder off the rear surface of the silver-backed glass mirror elements.
2. Heat ovens to bond the GOML (glass-on-metal-laminate) elements together.
3. A heated "clamshell" type mould that bonds the GOML and metal skins to the EPS core material, while maintaining the surface profile on the final mirror panel unit.

To these ends, the following possible designs have been developed to create these items.

Mirror cleaning tunnels

Fig. 34 shows a schematic of the functional elements of a continuous feed cleaning tunnel for the mirror elements.

As can be seen in the diagram, mirror blanks are fed into the tunnel from the input handling table, flexible entrance and exit flaps contain the working fluids within the confines of the cleaning tunnel, and a conveyor transport system moves the mirrors through a water jet cleaning section, an air drying jet system and finally a radiant heat drying section before exiting to the output handling table. Wash water is scavenged in a suitable tank, and reused after filtering to supply the cleaning liquid.

Radiant heat ovens

Fig. 35 shows a diagram of the radiant heat oven used to bond the mirrored glass onto the sheet-metal substrates. The oven consists of an insulated box, containing arrays of heat lamps placed above and below a sheet-metal mould, having the required curvature to impart a pre-curvature into the mirror panel elements during fabrication. The mirror panel elements (glass/fusible film/sheet-metal) are vacuumed onto the surface of the metal mould prior to heating. A alternative implementation has heating elements supported with fans for enhanced convective heat transfer to the mirror panel elements.

Heated clamshell mould for final, curved panel fabrication

Fig. 36 shows the clamshell mould for shaping and bonding the finished mirror panel. The mould can be made from either fibreglass or an egg-crate sub-structure and sheet-metal surface type structure.

As the figure shows, the clamshell design uses hinged male and female halves to clamp either side of the mirror panel. This design both holds the mirror panel to the required shape, and applies heat to accelerate the cure time of the adhesive used to bond together the sheet-metal and GOML elements either side of the EPS core material. Alternatively it can be used to bond the complete panel assembly using exclusively fusible film adhesives in a single process.

Production processes

The actual auxiliary process equipment required to manufacture mirror panels will depend on the production volume required. For low-volume runs (less than 1000 mirror panel units), it is expected that a large component of manual handling will be required in addition to the three major equipment items described above. In this instance, consumables and components will be manually transported between machinery for the different processing steps.

For unit volumes between 10,000 and 100,000 units, higher level automation equipment would be required. This would be incorporated in the consumables handling, and conveyor and pick-and-place transport systems would be installed between process steps to minimise manual manipulation of the components.

For unit volumes greater than 100,000, more complete automation would be required, with the installation of multiple lines of identical processing equipment.

In the cases of both the 10,000 unit and 100,000 unit scenarios, the handling systems will become as significant and costly, if not more so, as the three basic units (mirror cleaning, radiant heat oven & clamshell mould) described. In these eventualities, however, standard commercial systems would be installed from relevant manufacturers.

Industrial Applicability

The arrangements described are applicable to the power generation and optical instrument industries.

The foregoing describes only some embodiments of the present invention, and modifications and/or changes can be made thereto without departing from the scope and spirit of the invention, the embodiments being illustrative and not restrictive.

In the context of this specification, the word “comprising” means “including principally but not necessarily solely” or “having” or “including”, and not “consisting only of”. Variations of the word "comprising", such as “comprise” and “comprises” have correspondingly varied meanings.

APPENDIX A: SKIN MATERIALS

Material	Weight (kg/m^2 for 1mm thickness)	E (GPa)	Tensile stiffness / Cost ratio GPa.mm/($/m^2)	CTE x 10^6	Raw cost per m^2 (thickness)	Processed cost (over 200 dishes)	Comments
Z275 Galvabond	8.2	200 standard 250 measured	20 – 23 with raw cost 5 – 10 with processed cost ratio increases with thickness	~ 11.7	Range: $3.37 (0.35) - $8.62 (1.0)	~ $12 / m^2 for Ford stamping	Cheaper pressing under investigation
Colorbond	~ 7.9	200 standard 265 measured	13 – 14 with raw cost 4 - 7 with processed cost	~ 11.7	Range: $5.35 (0.35) - $11.46 (0.8)	~ $12 / m^2 for Ford stamping	Cheaper pressing under investigation. Prices for XRW Colorbond Also CRP available
Aluminium	2.8	70	5.5 with raw cost	24	Range: $15.23 (1.0) - $20.30 (1.6)	Not determined	
Luran S 797 S film	1.1	2	0.2 with raw cost (1 skin) 0.15 processed (2 skins)	95	$8.83 (1.0) (need 2 skins)	~ $10 / m^2 for Armacelling	UV stable but may not be suitable for Armacelling
Noryl 731 film	1.1	2.4		7.2	waiting on quote	~ $10 / m^2 for Armacelling	UV stable
PET film	1.3	2.7	0.8 with raw cost (1 skin) 0.3 processed (2 skins)	80	$3.20 (1mm)	~ $10 / m^2 for Armacelling	Not UV stable. Max thickness 0.5mm
Modar resin + glass fibre + filler	1.8	≥ 6 tensile ≥ 7.5 flexural (depends on filler content)	0.7 processed (using estimated cost of simple 5mm thick panel ~ $50/$m^2$)	18-33 (depends on glass content)		~ $50 / m^2 for 5mm thick panel (materials and processing)	Materials used in Resin Transfer Moulded panel
Woven Rovings +	2.0	9.6 calculated	0.2 with processed cost (2 skins)			~ $90 / m^2 for 2 skins (materials and processing)	Skin materials used in sandwich panel with Divinycell core

vinyleste r resin							

Table A.1

APPENDIX B: CORE MATERIALS

Material	Weight (kg/m²)	Density kg/m³	Tensile & Shear moduli MPa	CTE x 10^6	Raw cost per m²	Processed cost (over 200 dishes)	Comments
Cardboard	< 1 – 2		Experimental values ~ 1000 but crushing occurs		~ \$2 - \$5 depending on construction	Technique for forming not identified	Would need some form of protection (wax, resin, etc) Has ~ 8% moisture content, which can lead to warping if heated from one side.
Paper honeycomb	< 1		no data available.		~ \$4 for 30mm thick, 12mm cells	Only obtainable as flat sheets. Cannot biaxially bend	Would need some form of protection (wax, resin, etc)
Divinycell (PVC foam)	1.0 for 20mm H45	48 for H45	42 / 18 for H45	35	\$47 for 20mm H45 (small qty price)	Cannot mould.	
EPS (Expanded Polystyrene)	1.1 for 40mm VH grade	28 for VH grade	~ 9.5 for VH grade	50 – 70	\$7 for 40mm VH grade	\$13 for 40mm VH grade - moulded	VH grade is most dense & rigid available
Polyurethane foam	1.1 for 30mm of 36 kg/m³	36 is common	~ 5 for 36 kg/m³	45 - 65	\$18 for 30mm (medium qty price)	Not identified.	
Styrofoam (extruded	1.4 for 35mm of RTM grade	Range: 28 – 45 RTM grade is 40 kg/m³	20 / 5 for RTM grade	70	\$17 for 35mm of RTM grade	Cannot obtain moulded. Limited range of thicknesses.	Imported.

polystyr ene)							

Table B.1

APPENDIX C: PANEL MATERIALS

Values in Table C.1 below are for weight, cost etc are for the "most cost effective construction" unless otherwise stated. This is the construction (i.e. the combination of materials) which provides a flexural rigidity of 10,000 Nm (approximately) at the least cost. Where there is more than one construction which has approximately the same cost then one is chosen on the basis of some other feature (such as ease of fabrication). Colorbond (rather than Galvabond) used as the steel material in all cases.

The "Max deflection" values are those predicted for a total load (normal to the panel) of 150 Pa. They are obtained using a flat plate model of the panel – The deflection is reduced by approximately 25% if a shell model is used, in the case of an homogenous panel (effect on a panel with a frame or ribs not yet determined).

The modelling of the panels was done using the Strand7 finite elemnt modelling package. The plate surface was divided into ~ 300 elements unless otherwise specified. In Strand7 a choice is available between various different types of plate elements – the simplest is a "Tri3" (i.e. a triangular element defined by 3 points), which requires the least computational time. However when Tri3 elements are used the model with a composite material the program does not allow for coupling effects. Hence, unless specifically noted, all modelling was done using Tri6 elements. Note that in some cases the panel on its own was modelled using Tri3, but the panel with mirror (value in square brackets) using Tri6.

The "mean abs rot" column refers to the mean absolute rotation of all nodes on the plate (i.e. nodes on folds and frames are not included), which is closely corrlated with the mean slope error.

In all cases where the mirror is not bonded at the time of manufacture there will be an additional labour cost involved in attaching the mirrors – this has been approximated as $20 per panel, or $10 per square metre. The film cost of $2.50 per square metre has also been included where appropriate.

Prices do not allow for any mounting attachments.

Values for rigidity, deflection and rotation in square brackets are for the panel including the effect of the stiffness of the mirror. This is not necessarily the "correct" value to use as there may be more than one mirror surface across the face of the panel, or if any cracks appear in the mirror then some of the rigidity is lost. Note that a Tri6 element model "should" be used when the mirror is added, as the laminate becomes asymmetric and coupling can occur.

Values for the steel + EPS sandwich do not (except) for the weight include the effect of the mirror stiffness. Values for the various GOML combinations **do** include the stiffness of the mirror.

Note A: Armacel panel - If allow for the additional stiffness that results from the bonding of the mirror then a reduced thickness of EPS is required. With 50mm EPS get D = 52,000 Nm and max deflection = 1.1mm (note that this is a much higher deflection than would result from a symmetic laminate of that rigidity, due to coupling effects). Total cost would then be ~ $41/m^2$, as opposed to ~ $51/m^2$ with 90mm EPS. Rigidity, deflection and rotation values in the table are for the Armacel panel on its own.

Material	Most cost effective construction	Weight (kg/m^2) **incl. mirror**	Flexural Rigidity Nm	Max deflection mm	Mean abs rot (mrad)	Cost / m^2 (averaged over 200 dishes) – excluding mirror	Comments
Aerated Concrete (AAC)		18 for 30mm of 500 kg/m^3 dry weight (inital weight	~ 3000 for 30mm of 500 kg/m^3 (using *compressive* modulus of AAC)	> 4 (not modelled)		Can only obtain standard blocks & panels	Takes 8 hours to cure. High initial moisture content could lead to corrosion of mirrors.

		is higher)					
Armacel	1.0mm Luran + 90mm EPS (see note A above)	7.3	10,000	0.92	0.82	Estimated ~ $51 to $61 (see note A above)	Size of panel limited by film width. Waiting on quote for Noryl film.
Injection moulded plastic						Waiting on quote	
CCBM Divinycell panel	20mm Divinycell core	7.3	2,250 [11,000]	5.1 Tri3 [1.0]	4.4 Tri3 [0.9]	$180 - $200 for 1 dish quantity + mirror bonding	
RTM Modar resin panel	Fibreglass panel with flanges + ribs (no core)	13.8	85 excluding ribs [560] Used E = 7.5 GPa	13.3 Tri3 [5.3]	11.8 Tri3 [5.1]	$140	5mm thick panel; 20 x 10mm ribs & flanges. Deflection (with mirror) reduces to 3.6mm with 30 x 10mm.
SMC fibreglass panel						~ $115 + mirror bonding	Mechanical characteristics comparable to RTM. Cannot produce full size panel.
Steel + EPS sandwich	0.42mm steel skins + 14.5mm EPS	9.7	10,000	0.74	0.68	Estimated ~ $46	
GOML (with folded edges)	1.0mm steel	10.8	130 (experimental)	20 Tri3	17.5 Tri3	Estimated ~ $33	
GOML with folds + central ribs	0.8mm steel panel, 60 x 30 x 1 mm ribs	11.4		0.66 Tri6 1.1 Tri3	1.0 Tri6 2.0 Tri3	Estimated ~ $49 but no firm rib processing cost.	Max deflection 0.7mm & mean rotation = 1.7mrad for a *square* ribbed panel (Quad4)
GOML + wire frame	0.8mm steel Used SG3/2 frame design	17.0		~ 2 (not in centre)	~ 4	Estimated ~ $52 + on site assembly costs	Used 8mm diam wire for upper & lower frames. *May not need folded edges.*
GOML + pressed weldmesh	0.8mm steel 100 x 100 x 5.6 mesh - 25 high	15.0		3.4 Quad4 (not in centre)	5.7 Quad4	$40 to $45 + cost of pressing and attaching mesh	Modelled using a 1.4 x 1.4m SQUARE panel for simplicity.
Glass (hot	6.6mm thick	18	1850	5.3	4.7	Up to $400	

sagged)							

Table C.1

Appendix D

Projected production costs for dual metal skin, foam core, trapezoidal sub-panel manufacture.

Item costs per sq.m.	**Cost/$m^2**	%	**Trapezoid items**	**Value**	**Hours**	**No. of dishes**
Styrofoam	$13.00	9.73%	Area (m^2)	0.7		20
CB (2x0.35mm)	$20.00	14.97%	Press tool	$12,000.00		
Glass mirror	$20.00	14.97%	Junction tools	$6,000.00		
Fusible film	$5.00	3.74%	Number	12960		
Press&Operator costs/m^2 (x2 units)	$18.57	13.90%	Trapezoid pressing labour (per unit)	$6.50		
Press tool/m^2	$1.32	0.99%	Trapezoid assembly plant cost	$200,000.00		
Junction tools/m^2	$0.66	0.50%	Junction piece material area (m^2)	0.3		
Junction piece materials (CB, 0.8 mm, $18/m^2)	$5.40	4.04%	Labour costs/hr	$30.00		
Trapezoid assembly plant	$22.05	16.50%	Trapezoids assembled/hr	6		
Wastage	$5.00	3.74%				
Trapezoid assembly labour/m^2	$7.14	5.35%	**Triangle**			
Triangle assembly labour	$3.57	2.67%	Triangle assembly costs	$7.50	0.25	
Fastening systems	$5.51	4.13%				
Costs (excl. breakage)	$127.23	95.24%				
Breakage	$6.36		Fastening equipment	$50,000.00		
Total	**$133.59**	4.76%				
			Breakage rate	5%		
Dish surface area	453.6					
Mirror panel costs per dish	$60,595.75					
Notes:						
1. Styrofoam used for filler in metal trapezoid panels						
2. CB = colorbond						

3. Junction tools used for mounting trapezoids to form triangle. Costs estimated as fractional part (50%) of costs for trapezoid panel tooling costs.					
4. Trapezoid layup and handling estimated at 10 mins/trapeziod					
5. Trapezoid assembly plant estimated cost @ $200k for automation equipment and controls					
6. Assembly of 3 trapezoids into 1 triangle estimated at 15 mins/triangle					
7. Henrob fastening system estimated by Custom Ladder Co. at $25k-$50k					

Claims:

1. A solar mirror sandwich panel, comprising:

a reflective lamina component having a reflective surface that has an average slope error of less than or equal to about 6 milliradians;

two metal skin components for stiffening the solar panel, and

a core filler component disposed between the metal skin components;

wherein said components are bonded together using adhesive and are arranged in a curved configuration to provide a curved solar panel.

2. A solar mirror sandwich panel, comprising:

a reflective lamina component having a reflective surface formed on side of said reflective lamina component;

two metal skin components for stiffening the solar panel, and

a core filler component disposed between the metal skin components, said core filler component being material selected from the group consisting of expanded polystyrene, paper honeycomb, fibreboard, and cardboard;

wherein said components are bonded together using adhesive and are arranged in a curved configuration to provide a curved solar panel.

3. The panel as claimed in claim 1, wherein the core filler component comprises at least one of a polymer, paper honeycomb, plastics, and cardboard.

4. The panel as claimed in any one of claims 1 to 3, wherein the reflective lamina component comprises a glass sheet with a mirror backing.

5. The panel as claimed in claim 4, wherein the glass sheet has a thickness of less than about 2 mm.

6. A solar mirror sandwich panel according any one of claims 1 to 2, further wherein a thickness of said core filler component is between about 5 millimetres and about 100 millimetres.

7. The panel as claimed in any one of claims 1 to 6, wherein said metal skin components comprise a steel sheet having a thickness between about 0.2 mm and 1.0 mm.

8. The panel as claimed in any one of claims 1 to 6, wherein said metal skin components comprise a steel sheet having a thickness between about 0.2 mm and 1.0 mm and which has a corrosion protection coating based in part on a zinc and aluminium formulation.

9. The panel as claimed in claim 1, wherein the metal skin components comprise the same materials.

10. The panel as claimed in claim 1, wherein the metal skin components have the same thickness.

11. The panel as claimed in any one of claims 1 to 10, wherein the components are bonded using one or more adhesives.

12. The panel as claimed in any one of claims 1 to 10, wherein the components are bonded using fusible film.

13. The panel as claimed in any one of claims 1 to 10, wherein the components are bonded using hot melt adhesive.

14. The panel as claimed in any one of claims 1 to 10, wherein the components are bonded using a fusible Ethyl Vinyl Acetate film having a fusing temperature of approximately 100 Degrees Centigrade.

15. A method of making a solar mirror panel, the method comprising the steps of:

providing an assembly comprising a reflective lamina component having a reflective surface, two metal skin components, a core filler component located between the metal skin components, and adhesive materials disposed between said components;

conforming the components to a mould having an at least partially curved surface in contact with said components, and

controllably heating at least part of at least one surface of the mirror panel to heat the adhesive material disposed between the core filler component and each of the reflective lamina component and the metal skin components, without heating the bulk mass of the core filler component.

16. The method as claimed in claim 15, wherein the step of controllably heating at least part of at least one surface of the mirror panel comprises applying heat using a heated body in contact with said metal skin component to set the adhesive between said metal skin components and core filler components.

17. The method as claimed in claim 15, wherein the step of controllably heating at least part of at least one surface of the mirror panel comprises applying heat using a heated body in contact with said reflective lamina and metal skin components to set the adhesive between said reflective lamina and skin and core filler components.

18. The method as claimed in claim 15, wherein the step of controllably heating at least part of at least one surface of the mirror panel comprises applying heat using a radiant heat lamps directed at said reflective lamina and metal skin components to set the adhesive between said reflective lamina and skin and core filler components.

19. The method as claimed in claim 15, wherein the step of controllably heating at least part of at least one surface of the mirror panel comprises applying heat using a hot oven with forced convection to transfer heat to said reflective lamina and metal skin components to set the adhesive between said reflective lamina and skin and core filler components.

20. The method as claimed in any one of claims 17, 18, or 19, wherein the rate of heating and amount of heat applied to said reflective lamina and metal skin components to set the adhesive between said reflective lamina and skin and core filler components is optimised so that the process is completed before the core material has become hotter than its own softening point.

21. The method as claimed in claim 15, wherein a thickness of said core filler component is between about 5 millimetres and about 100 millimetres.

22. The method as claimed in any one of claims 15 to 21, wherein a single adhesive is used between adjacent components.

23. The method as claimed in any one of claims 15 to 21, wherein two or more adhesives are used.

24. The method as claimed in any one of claims 15 to 21, wherein the adhesive material comprises fusible film.

25. The method as claimed in any one of claims 15 to 21, wherein the adhesive material comprises a hot melt adhesive.

26. The method as claimed in any one of claims 15 to 21, wherein said heated body comprises a metal sheet.

27. The method as claimed in any one of claims 15 to 26, wherein said core filler component comprises expanded polystyrene (EPS).

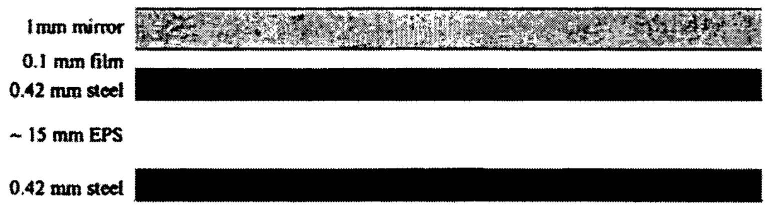

Figure 1. Cross section of sheet metal + EPS sandwich panel (not to scale)

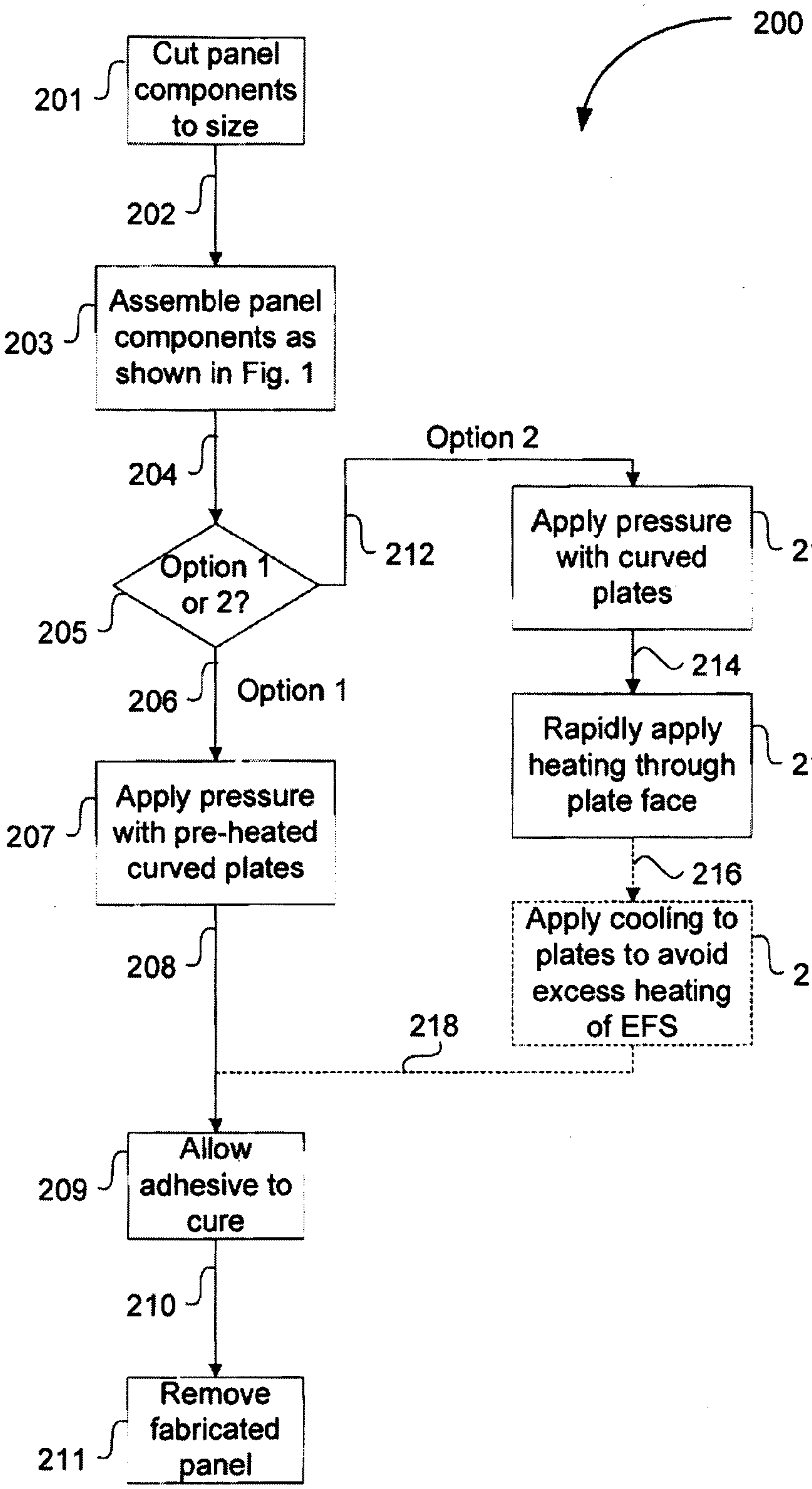
200
Cut panel components to size
201
202
Assemble panel components as shown in Fig. 1
203
204
Option 2
212
Option 1 or 2?
205
206
Option 1
Apply pressure with curved plates
213
214
Rapidly apply heating through plate face
215
216
Apply cooling to plates to avoid excess heating of EFS
217
Apply pressure with pre-heated curved plates
207
208
218
Allow adhesive to cure
209
210
Remove fabricated panel
211

Fig. 2

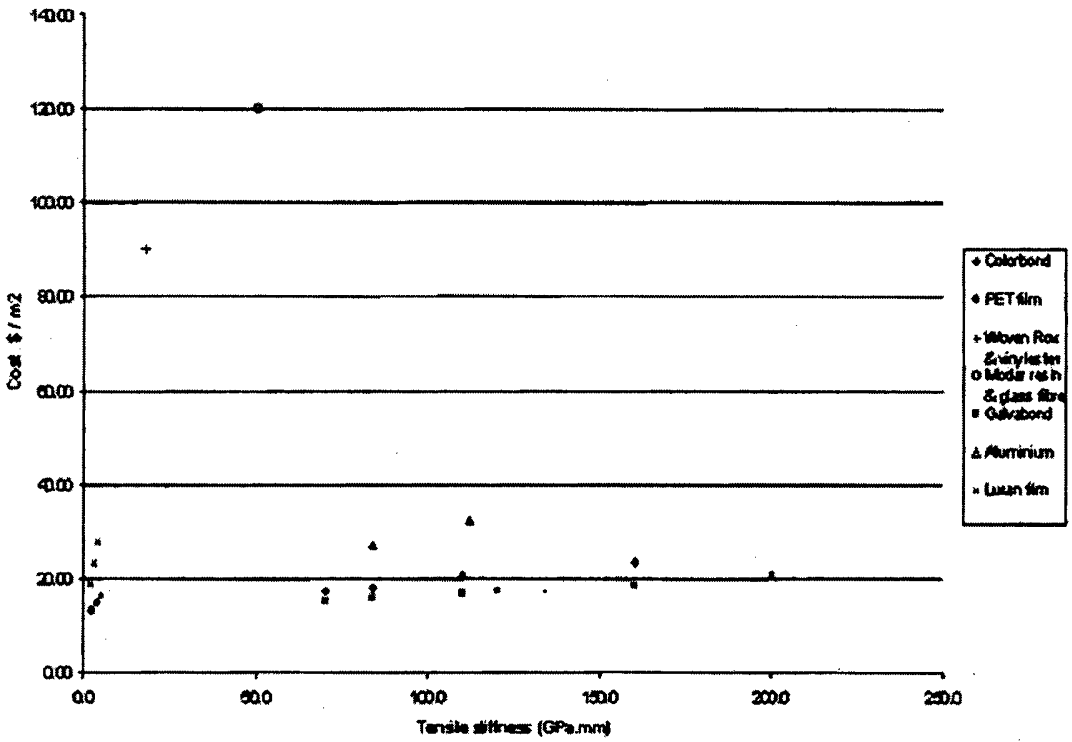

Figure 3. Plot of areal cost vs. tensile stiffness for a range of possible skin materials. PET = Polyethylene film

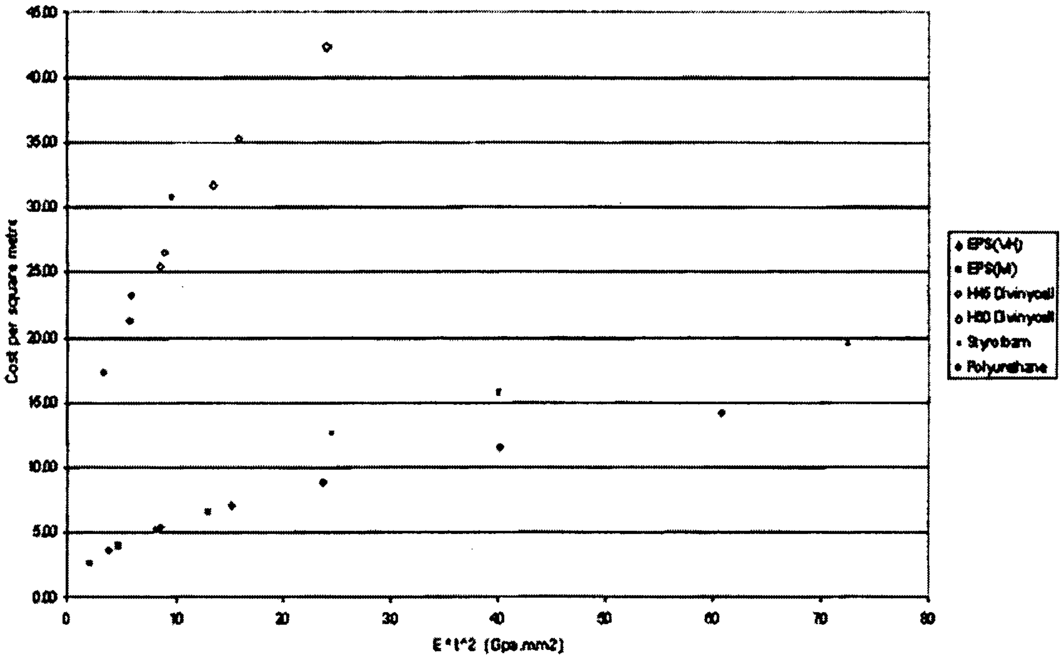

Figure 4. Plot of areal cost vs. E.t2 (a measure of flexural rigidity) for a range of possible filler materials (EPS = Expanded Polystyrene).

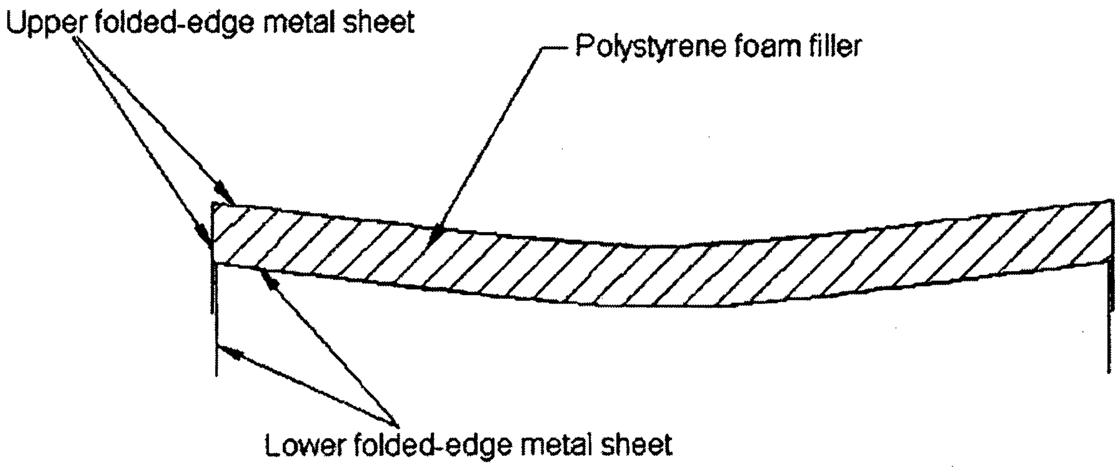

Figure 5. Cross-section through double sheet metal skinned, polystyrene foam filled panel.

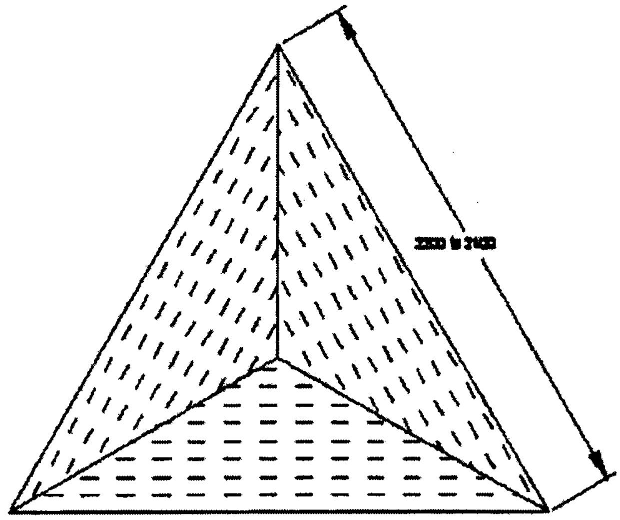

Figure 6. Equilateral triangular mirror panel constructed of 3 identical short isosceles triangles.

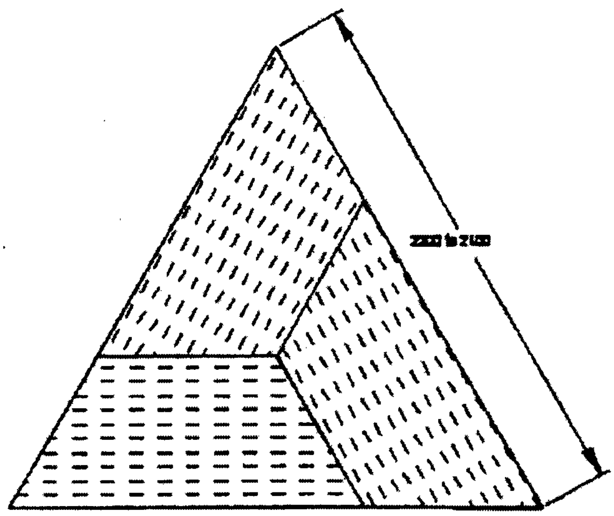

Figure 7. Equilateral triangular mirror panel constructed of 3 identical trapezoids.

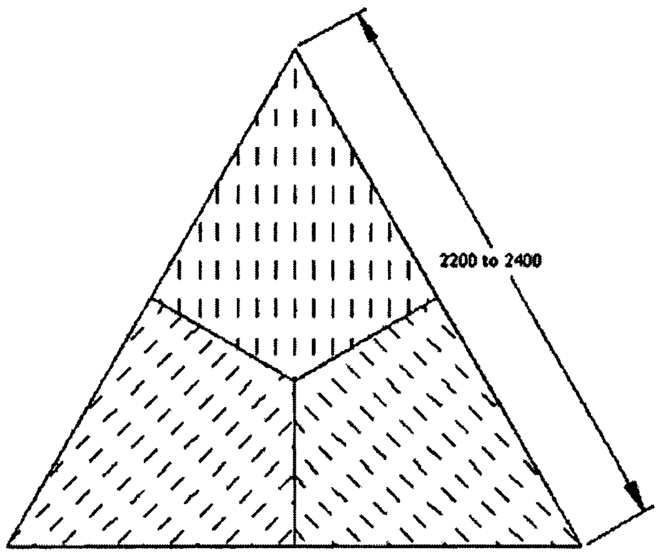

Figure 8. Equilateral triangular mirror panel constructed of 3 identical trapeziums.

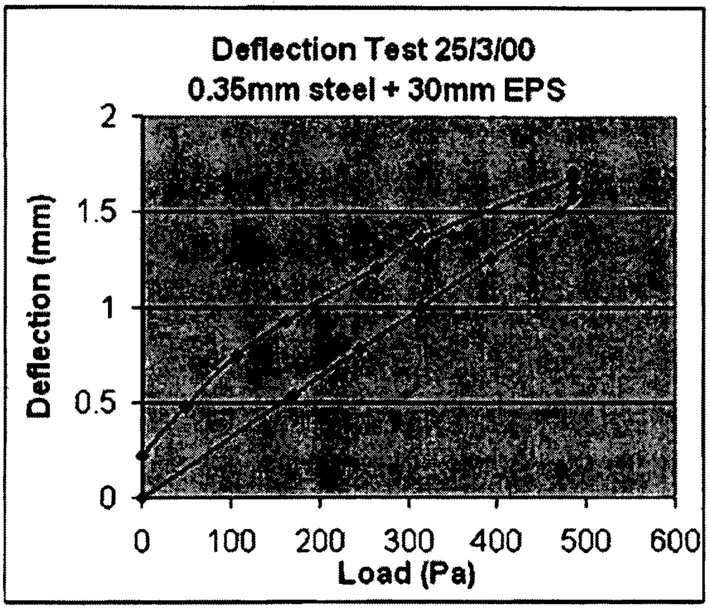

Figure 9. Deflection tests for a 1.2 m x 1.2 m dual skin, foam core panel. The lower curve corresponds to deflections that occur for an increasing load, while the upper curve indicates deflections while the panel is being unloaded after approximately 20 hours of static load at the maximum loading level (500 Pa).

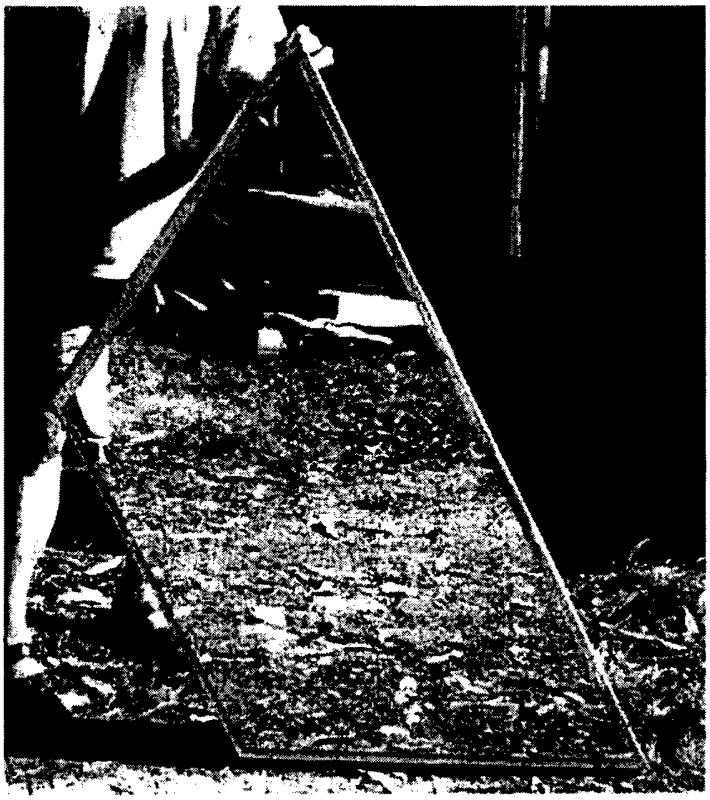

Figure 10. Comparative view of hand-made trapezoidal sub-panel.

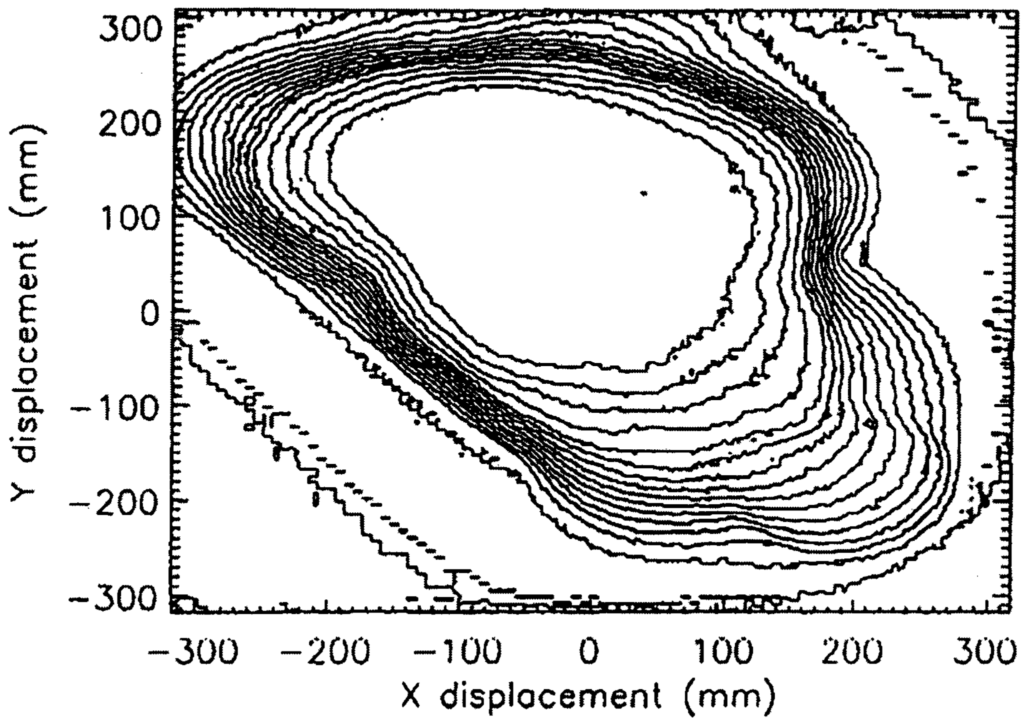

Figure 11. Contour plot of a flux distribution.

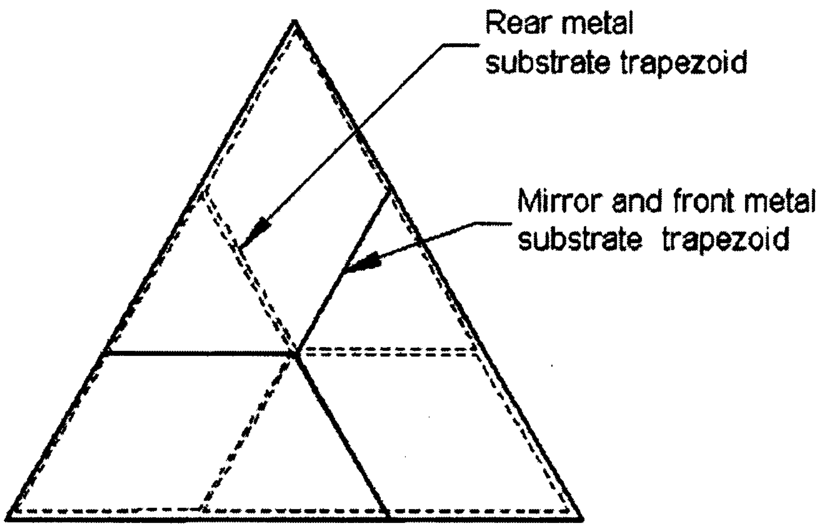

Figure 12. Foam-filled dual metal skin trapezoidal mirror panel with out-of-phase trapezoidal metal substrates.

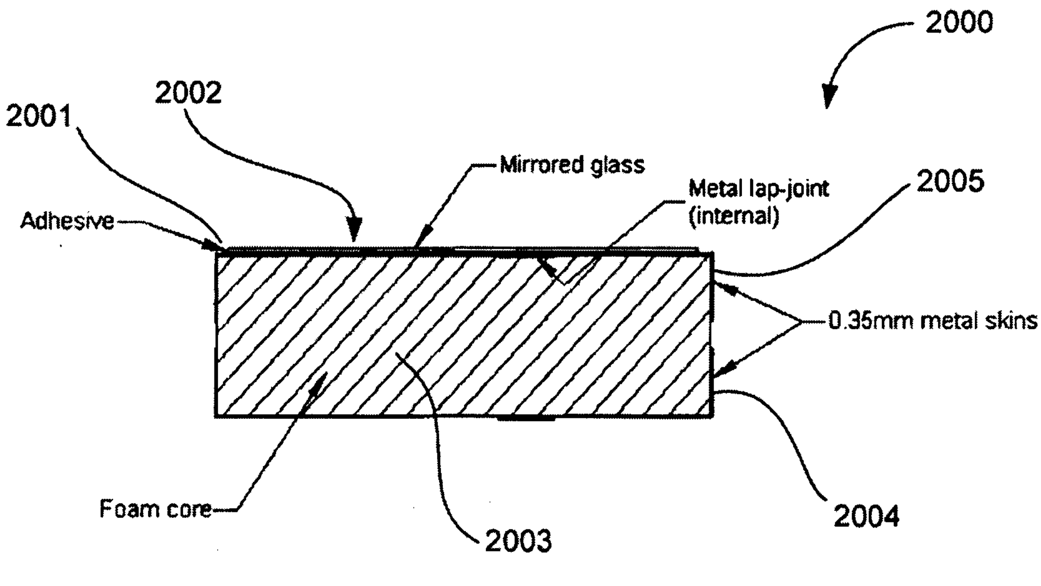

Figure 13. Lay-up of a foam-filled metal panel, showing front and rear metal skins, foam core and mirrored glass laminated onto the front metal skin.

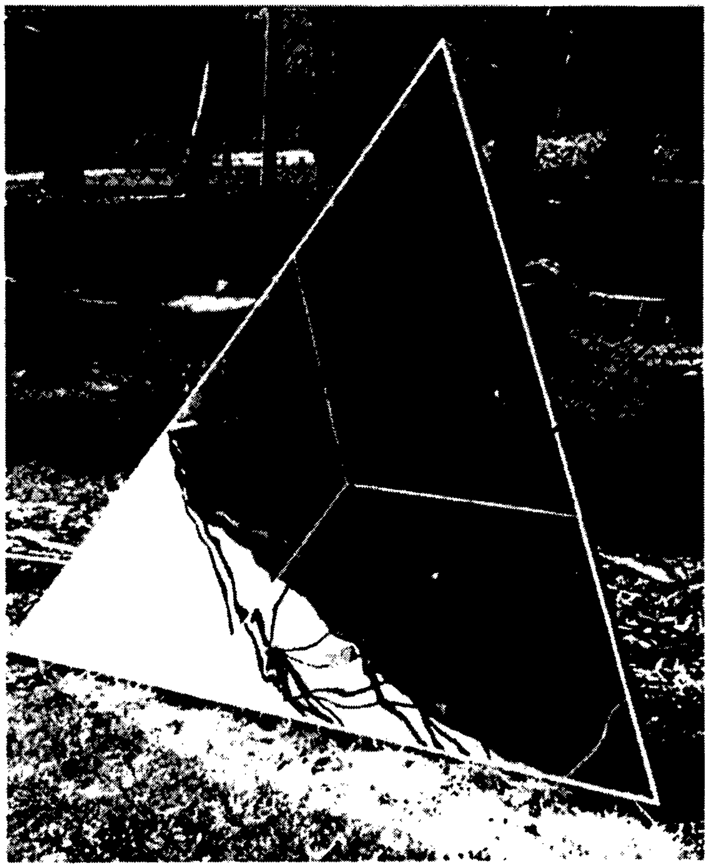

Figure 14. Front view of a foam-filled mirror panel triangular prototype.

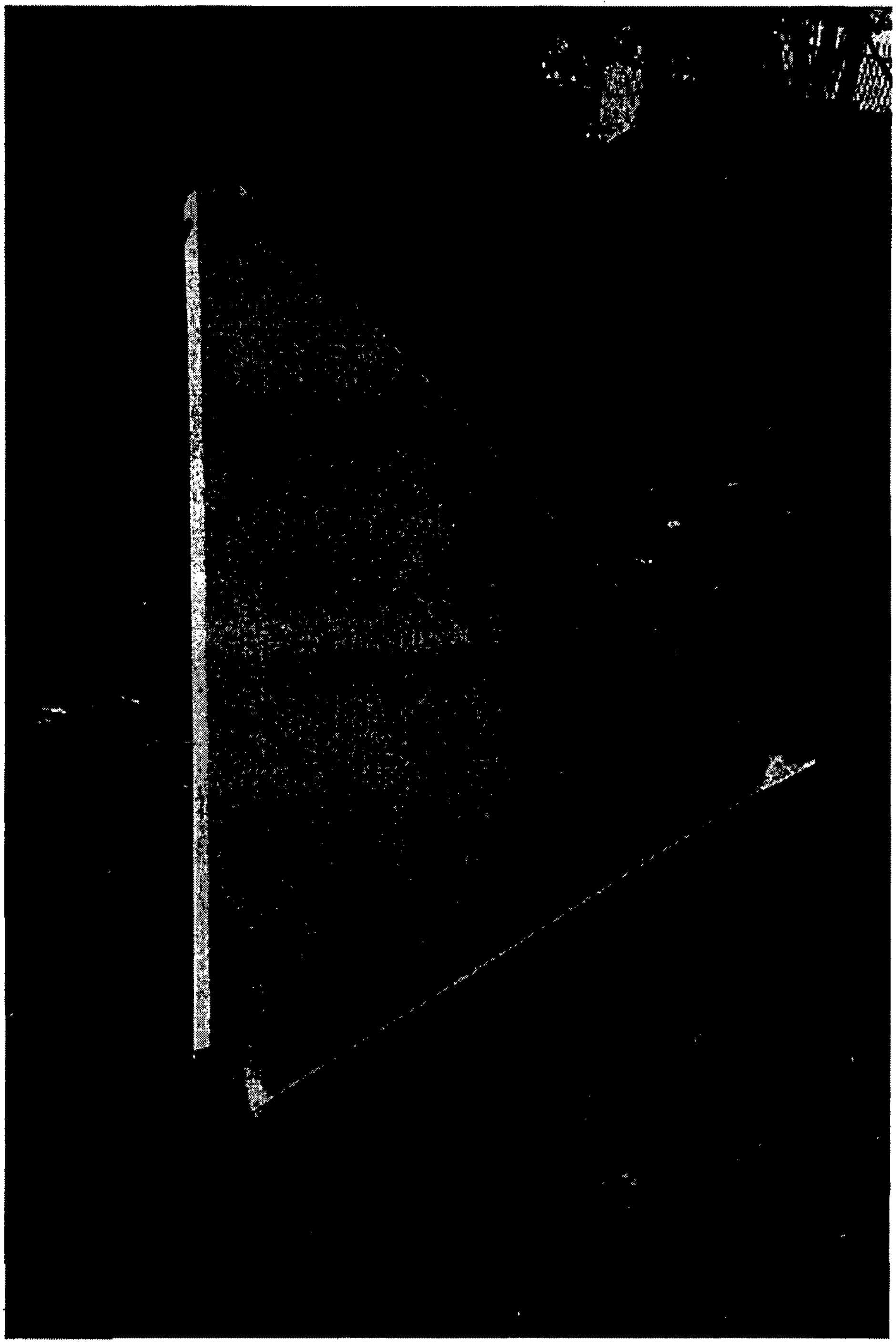

Figure 15. Rear view of the foam-filled mirror panel of Fig. 14.

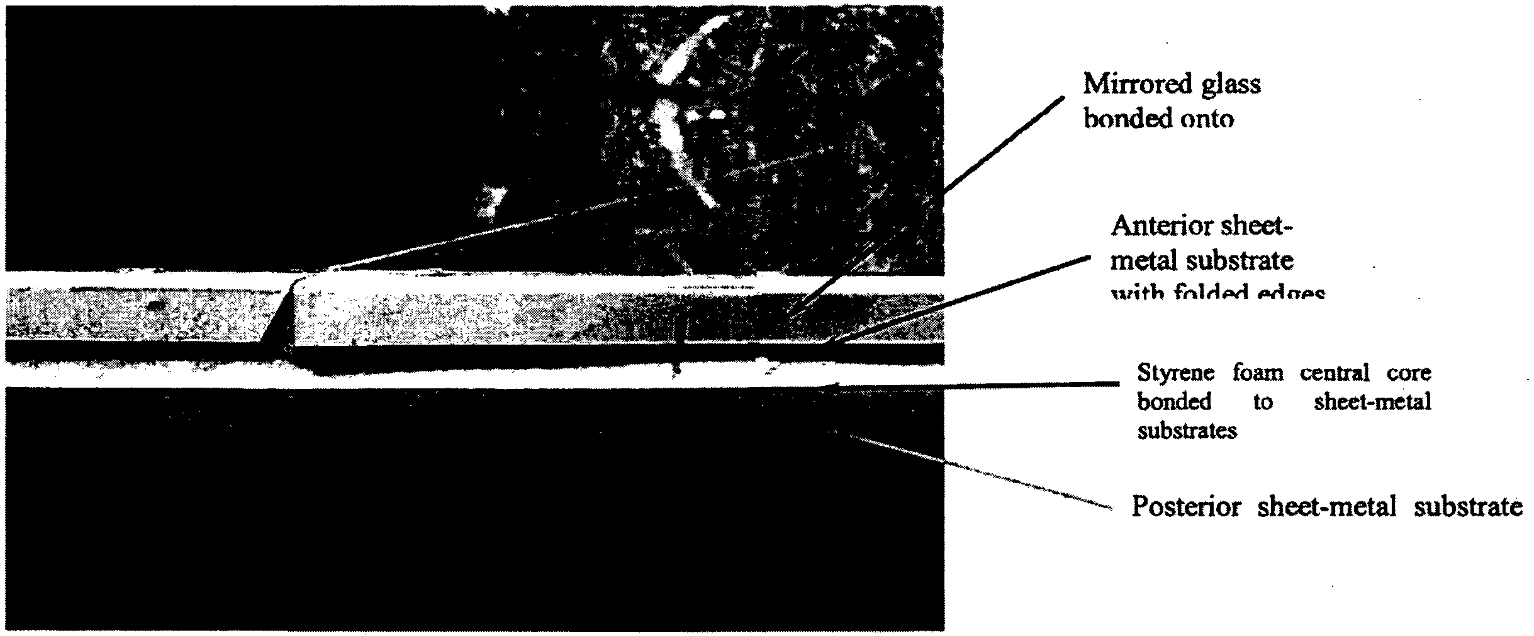

Figure 16. Edge view of foam-filled mirror panel, showing mirrored glass, folded sheet-metal edges and foam core.

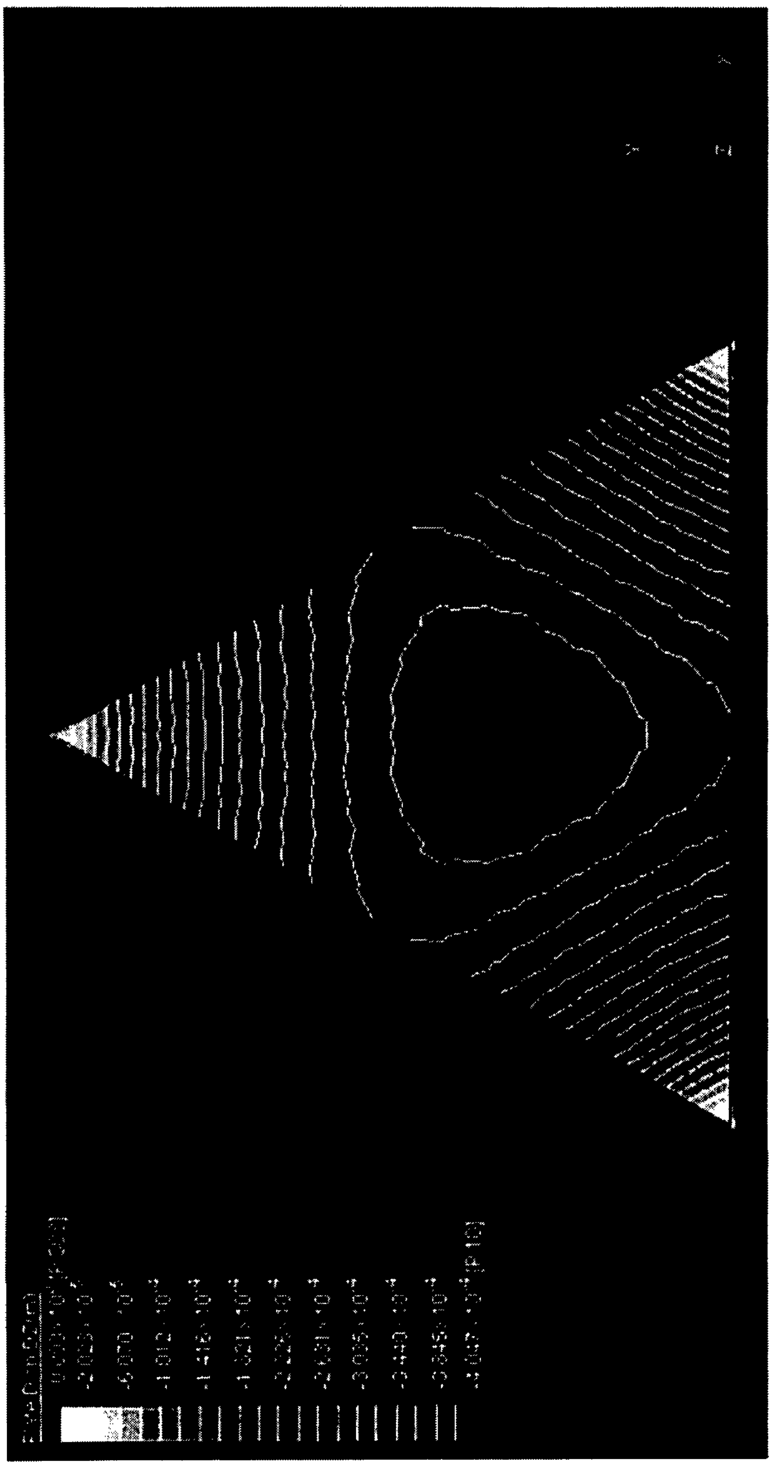

Figure 17. Predicted surface deflection characteristics for the foam-filled mirror panel using Strand 7 FEM modelling software.

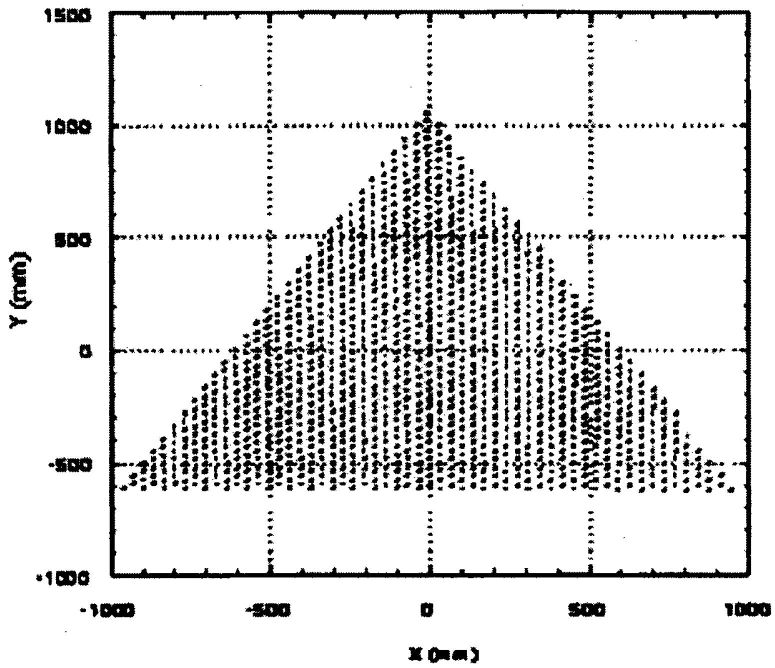

Figure 18. Layout of approximately 1200 data points used for photogrammetric analysis of the foam mirror panel surface quality.

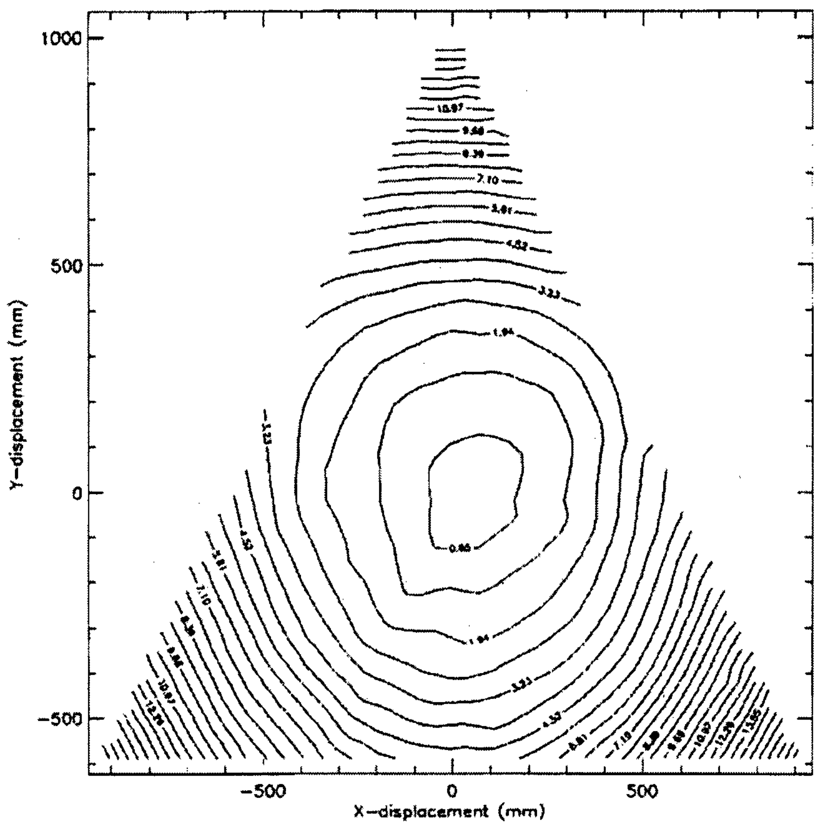

Figure 19. Contour plot of the foam mirror panel (of Fig. 14) surface shape determined from the photogrammetric analysis.

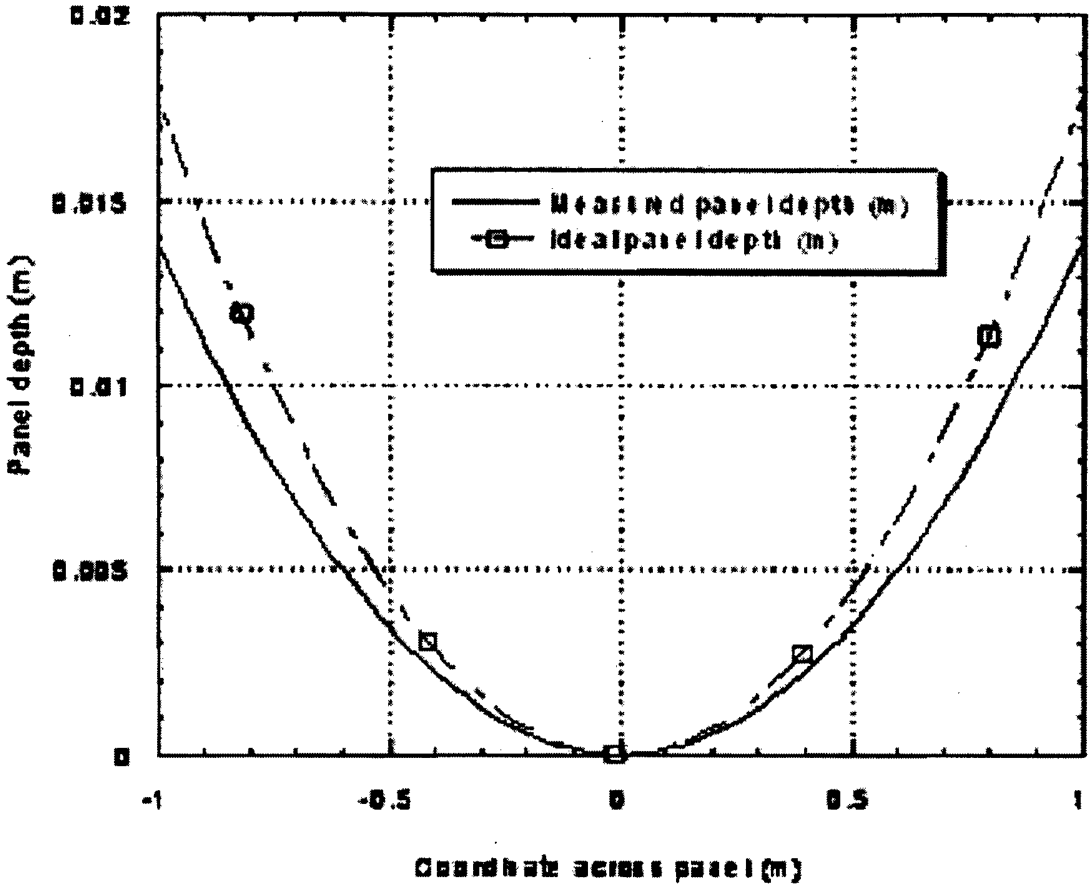

Figure 20. Plot showing the relative depth coordinate deviations between the measured paraboidal data and an ideal paraboloid (f=14 m) based on data in Fig. 19

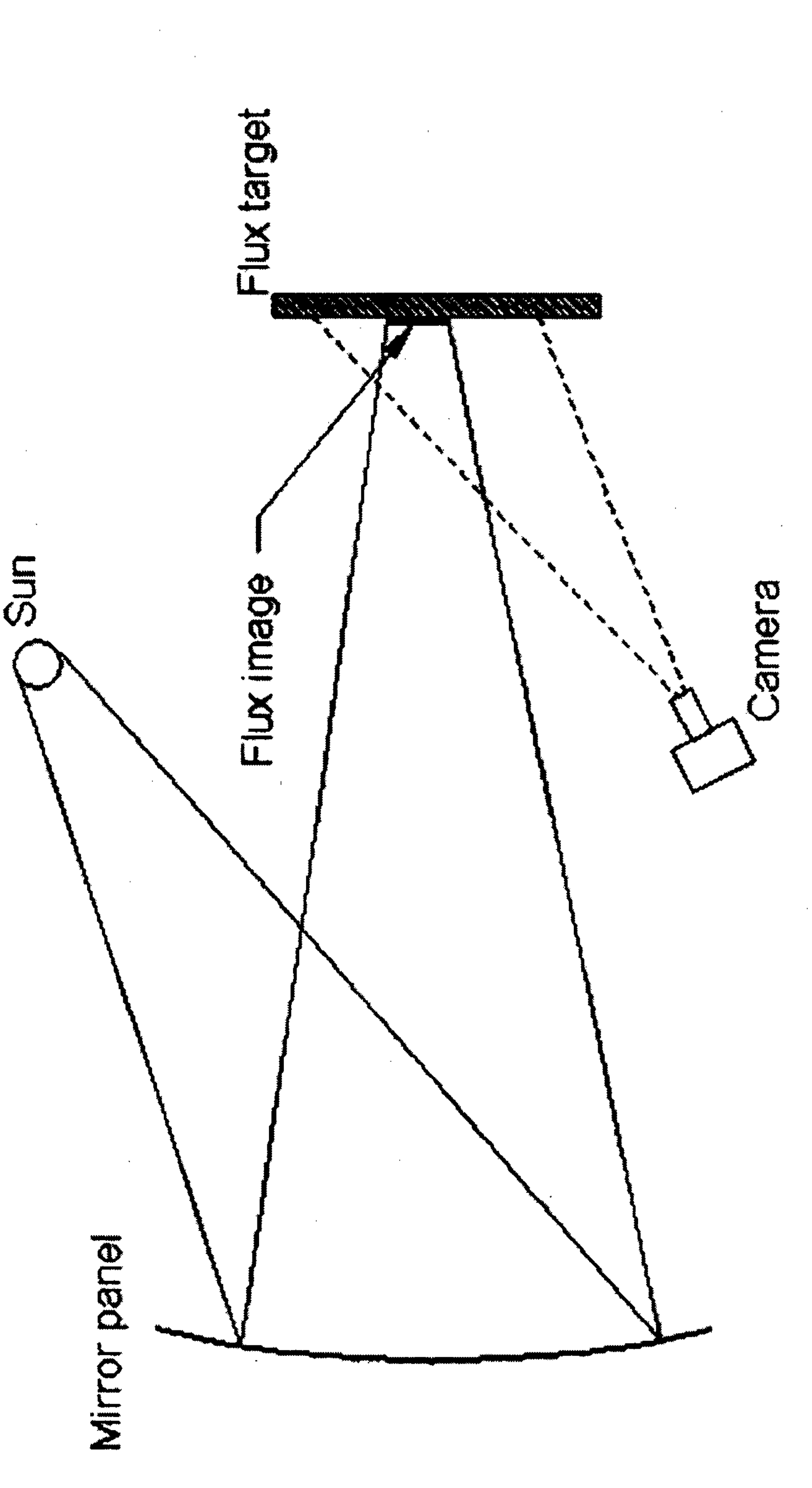

Figure 21. Layout of flux mapping equipment and measurement components (sun, mirror panel, target, etc.)

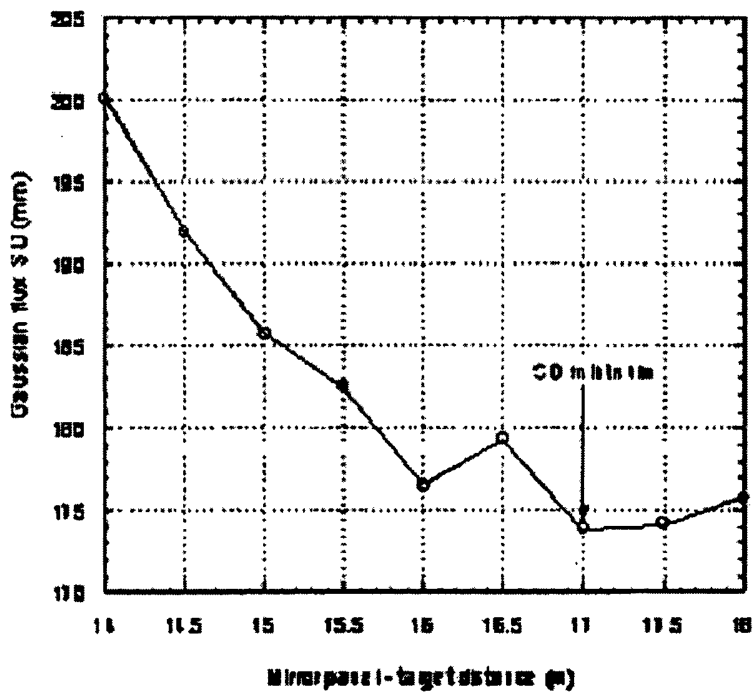

Figure 22. Plot of variation of flux image gaussian standard deviation as a function of mirror panel-to-target distance for the foam mirror panel flux image.

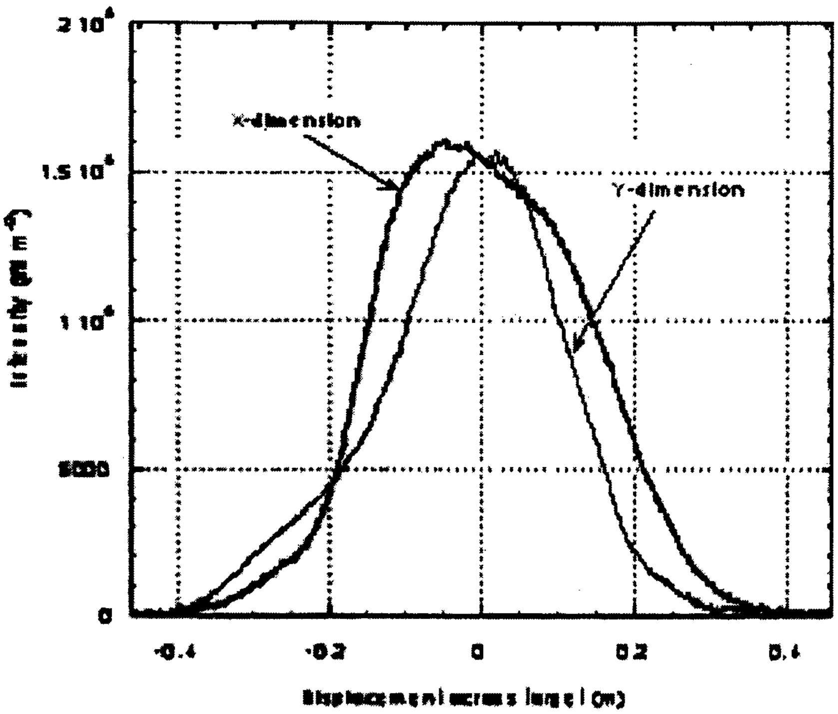

Figure 23. X and Y cross sections through the flux intensity distribution

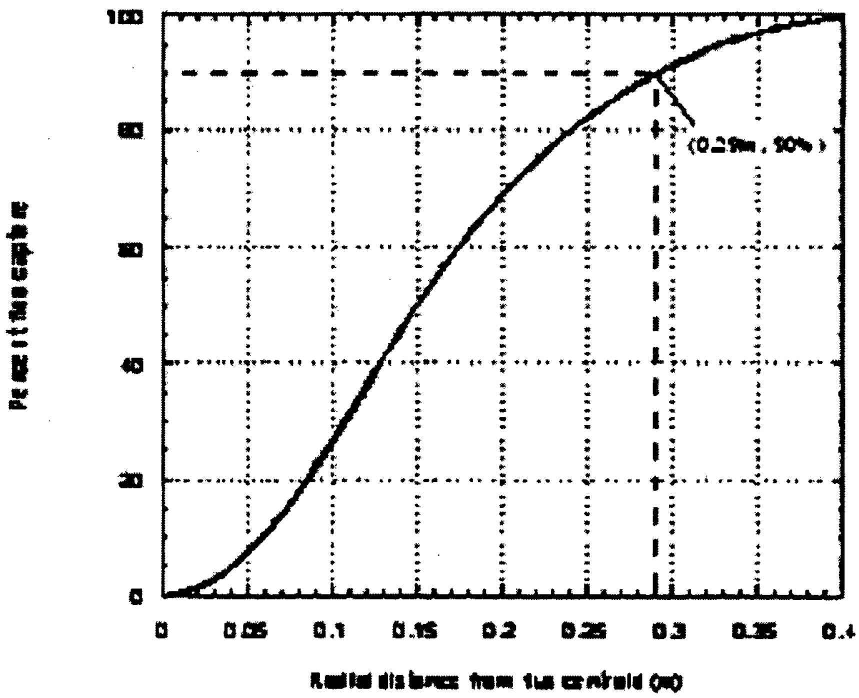

Figure 24. Percent-Power-In-Radius (PIR) plot for the flux

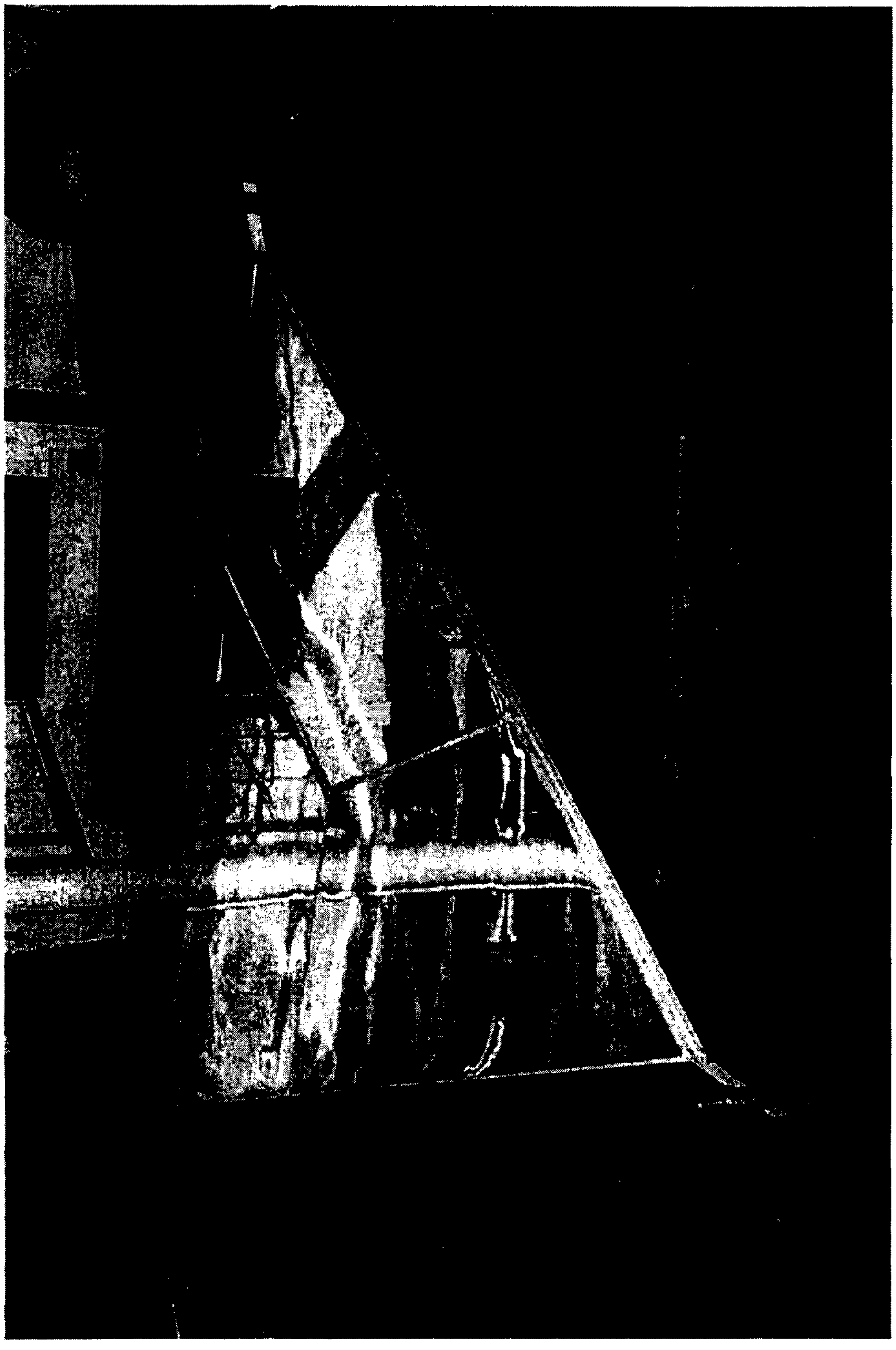

Figure 25. Hot-laminated glass-on-metal-laminate (GOML) foam-core mirror panel on mounting frame.

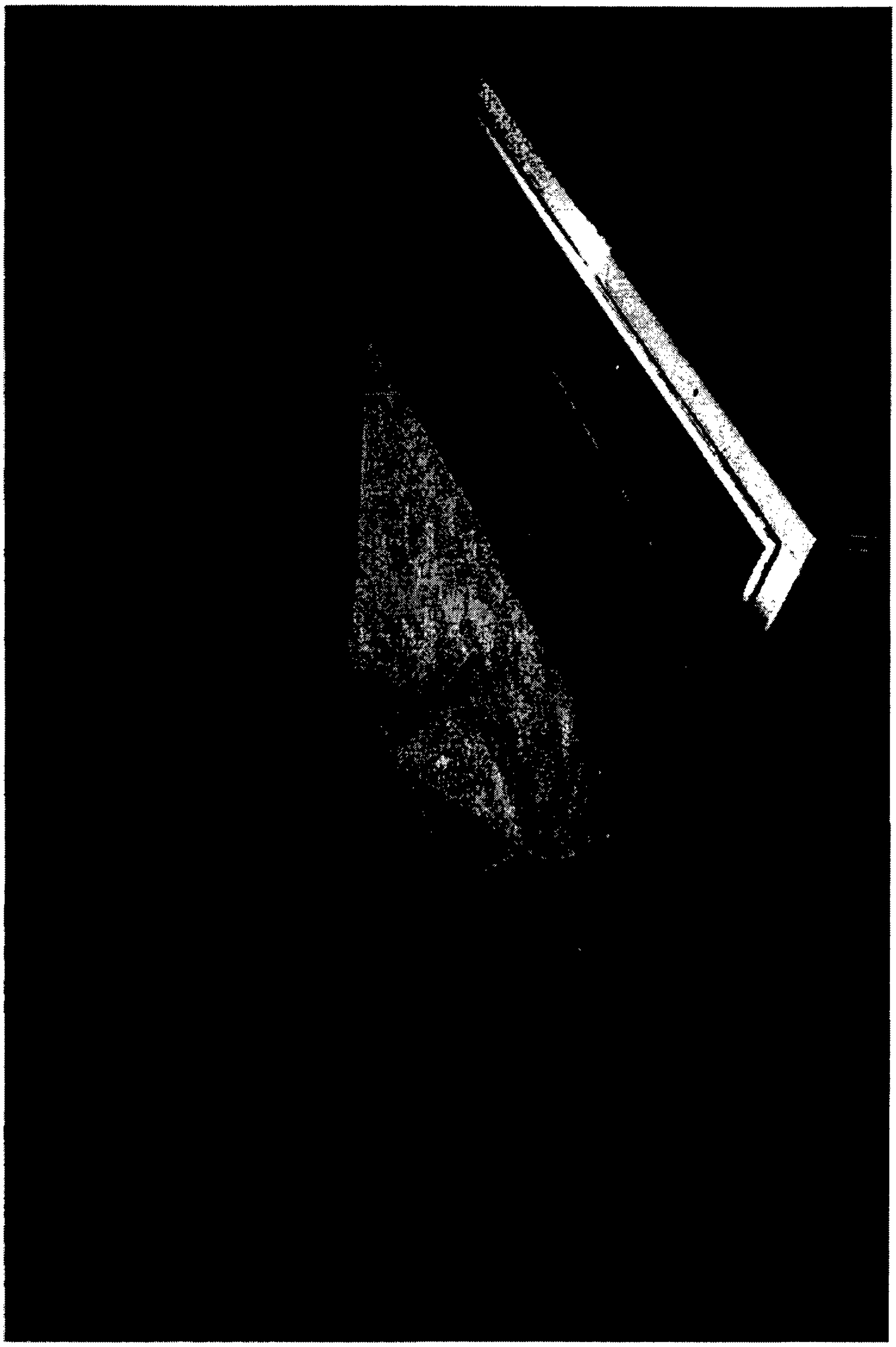

Figure 26. Spherical fibre-glass mould in oven with trapezoidal mirror facet and vacuum bag.

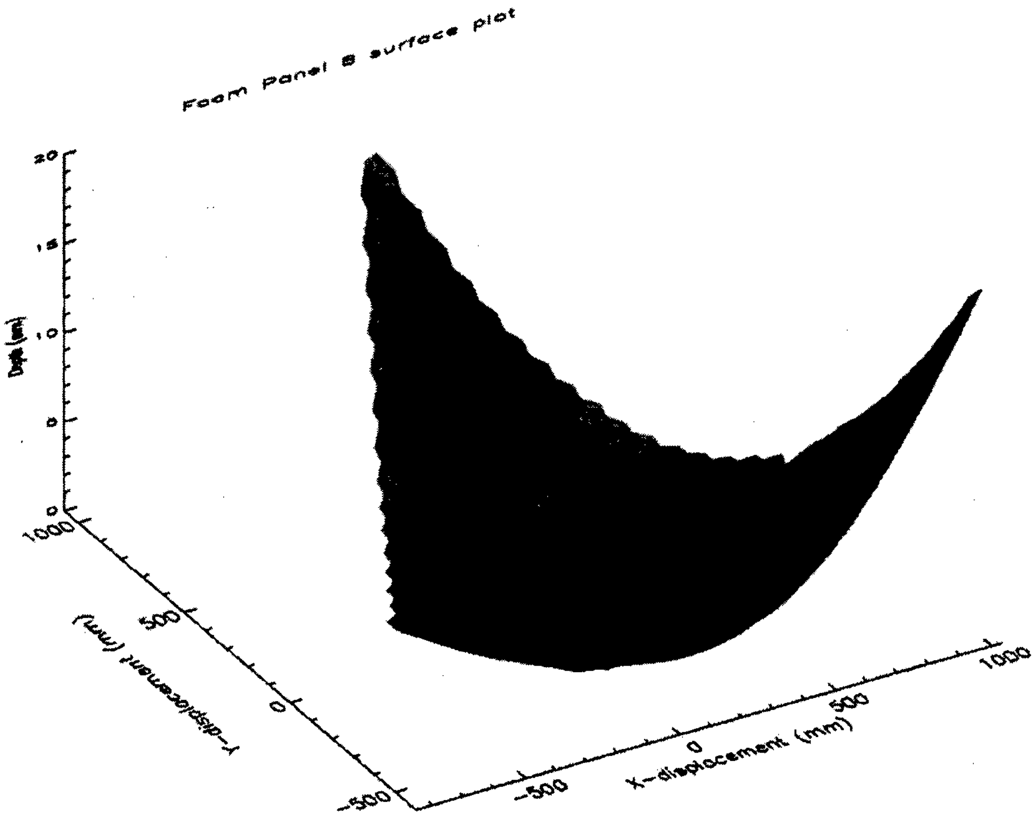

Figure 27. Surface plot for the triangular mirror panel shown in Fig. 25.

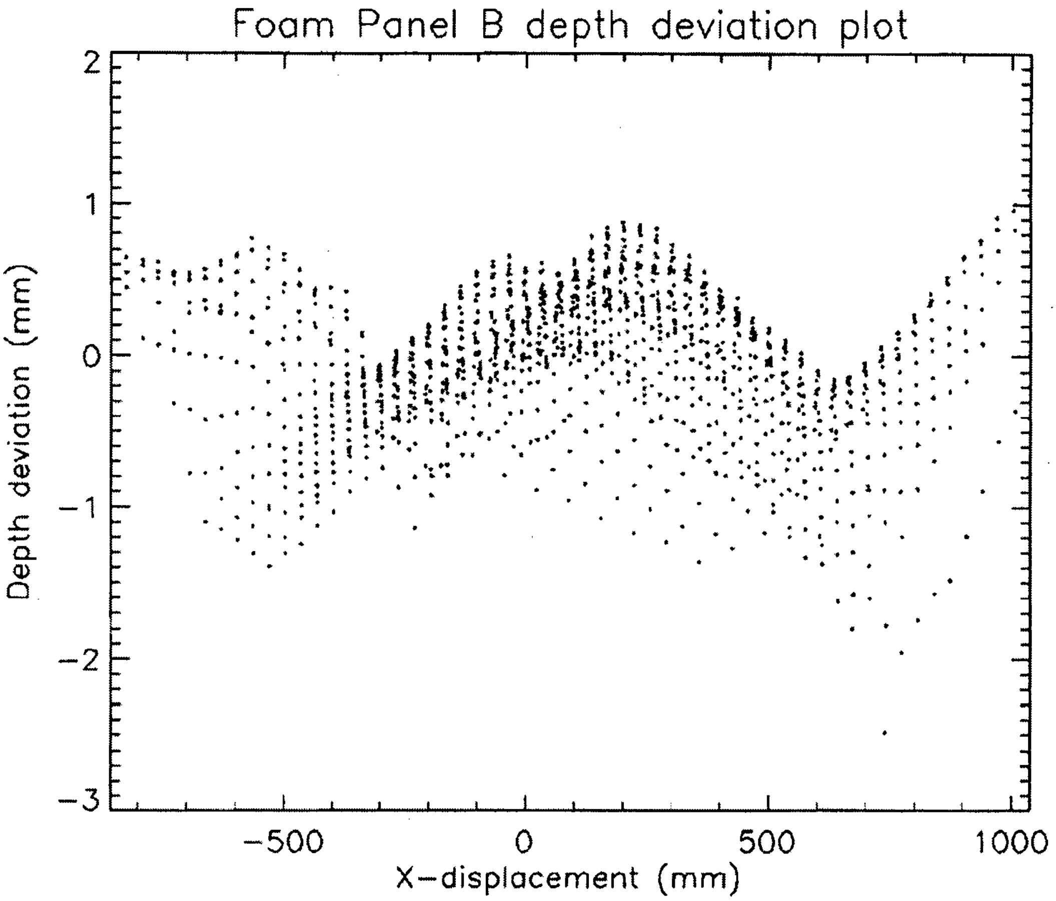

Figure 28. Plot of depth deviation data for ideal surface (ROC=35.28m) subtracted from measured depth coordinates of Fig. 25.

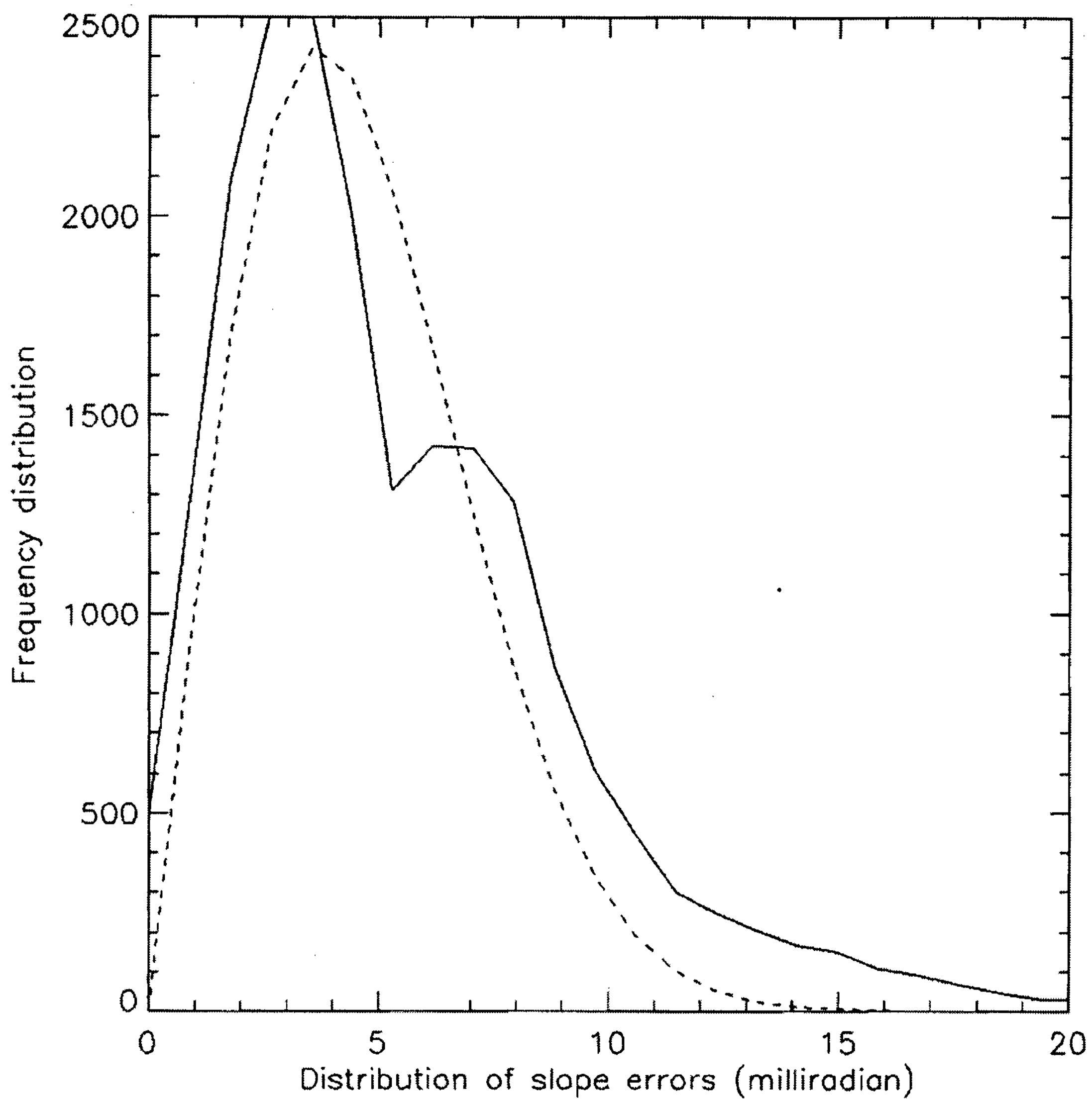

Figure 29. Frequency distribution of surface slope errors across the mirror panel of Fig. 25.

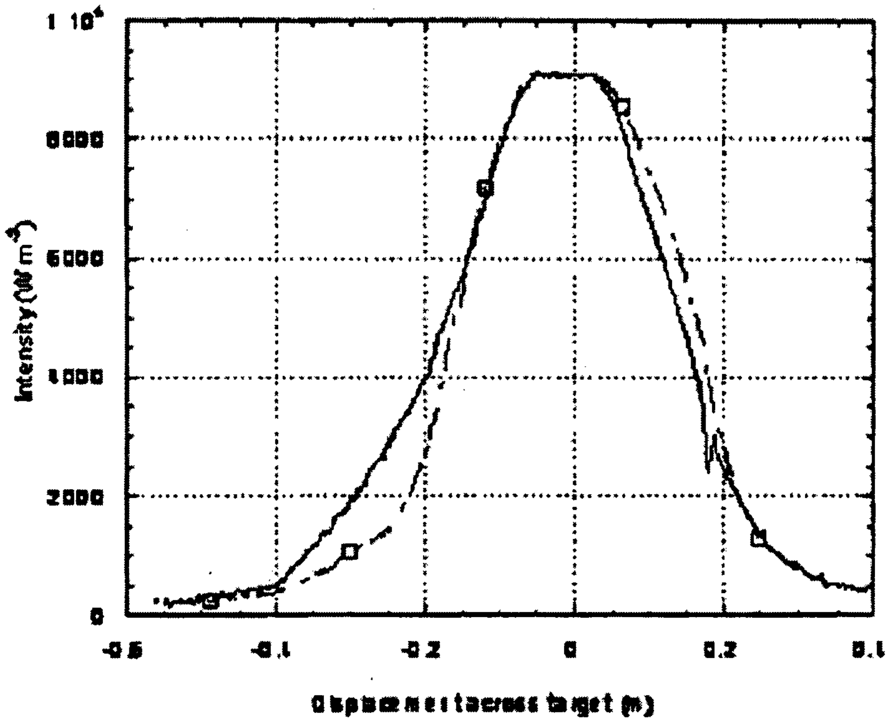

Figure 30. X- and Y-cross-sections through a measured flux distribution of Fig. 25.

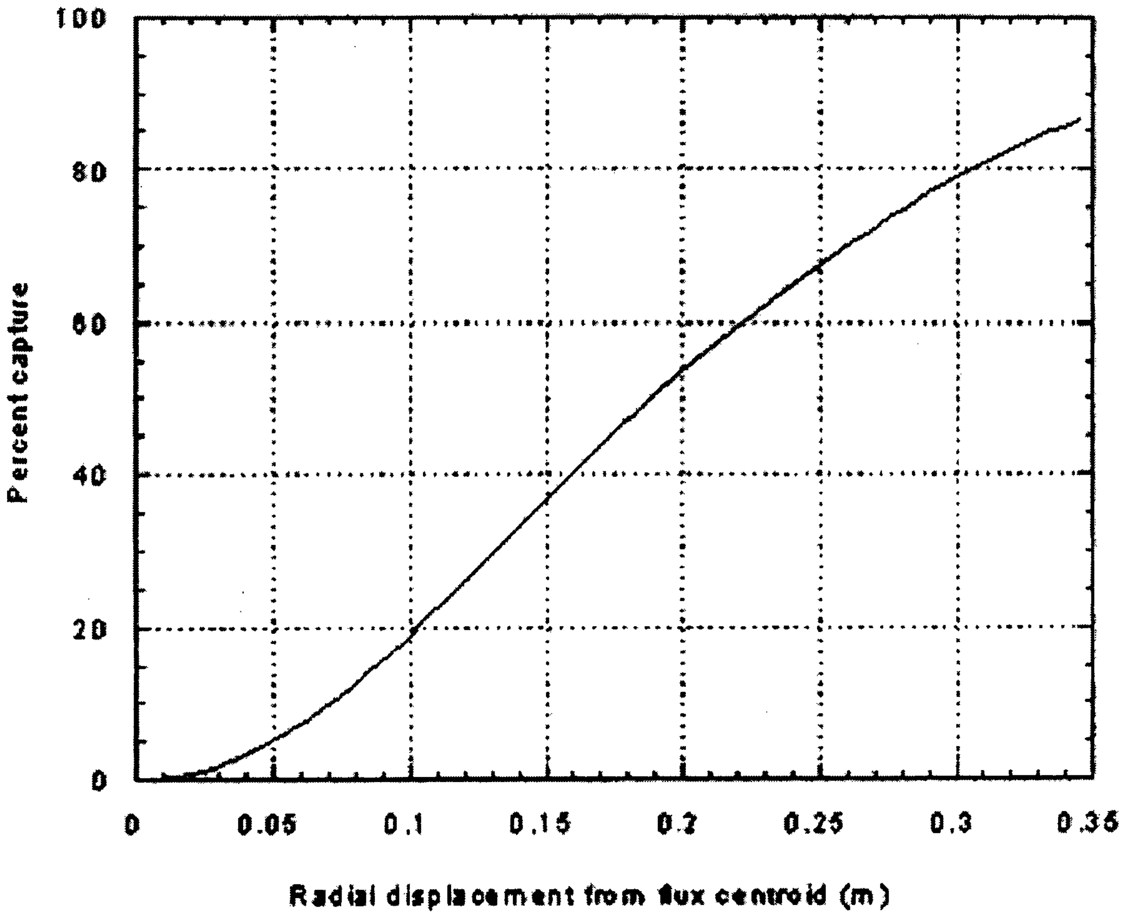

Figure 31. Percent power-in-radius (PIR) plot for the flux distribution of Figure 30.

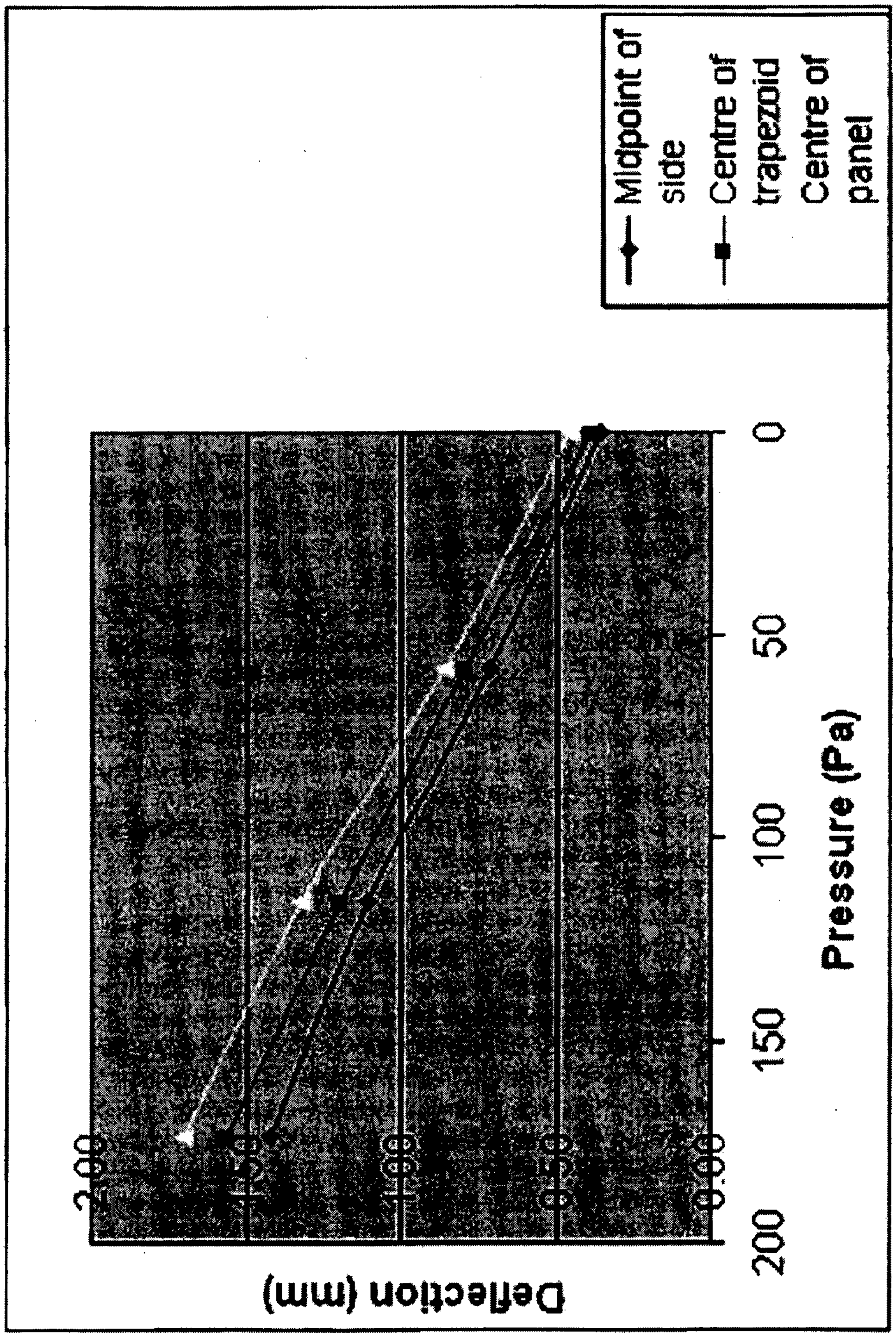

Figure 32. Deflections at 3 locations on the surface of the mirror panel of Fig. 25 as a function of equivalent hydraulic loading pressure.

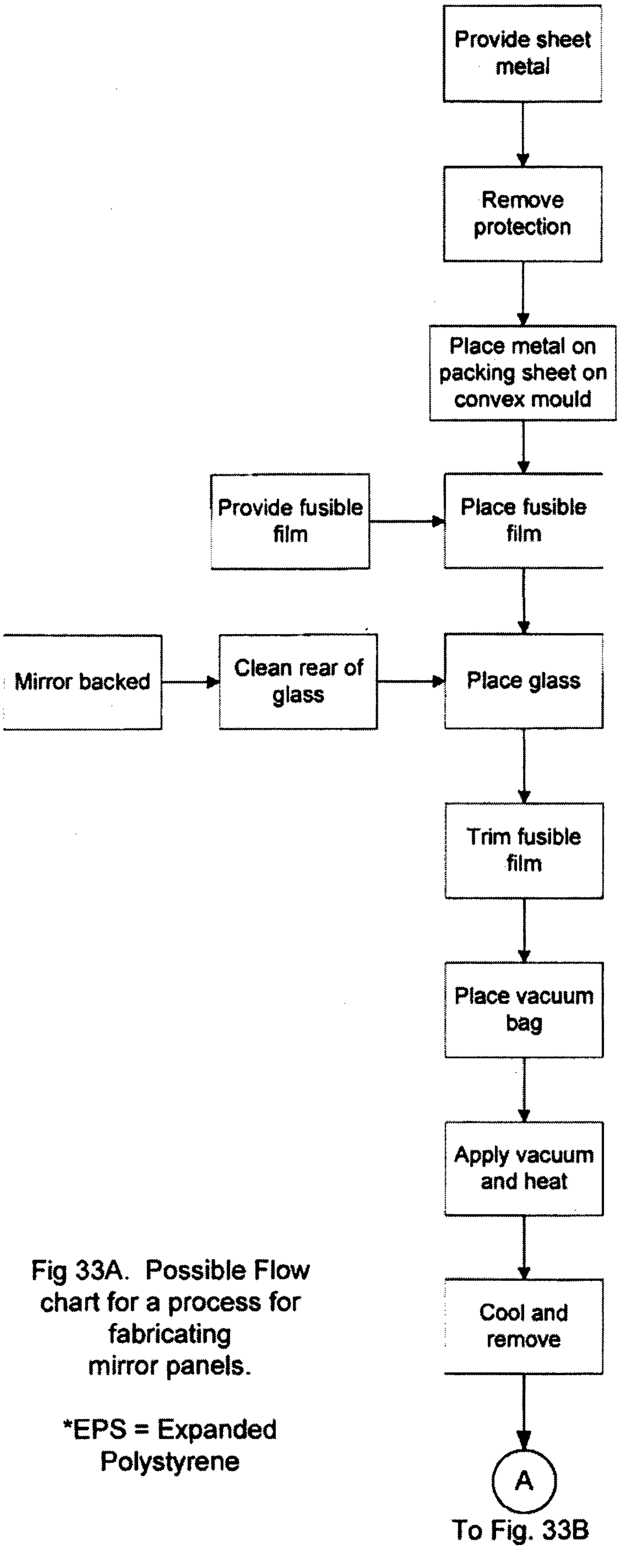

Fig 33A. Possible Flow chart for a process for fabricating mirror panels.

*EPS = Expanded Polystyrene

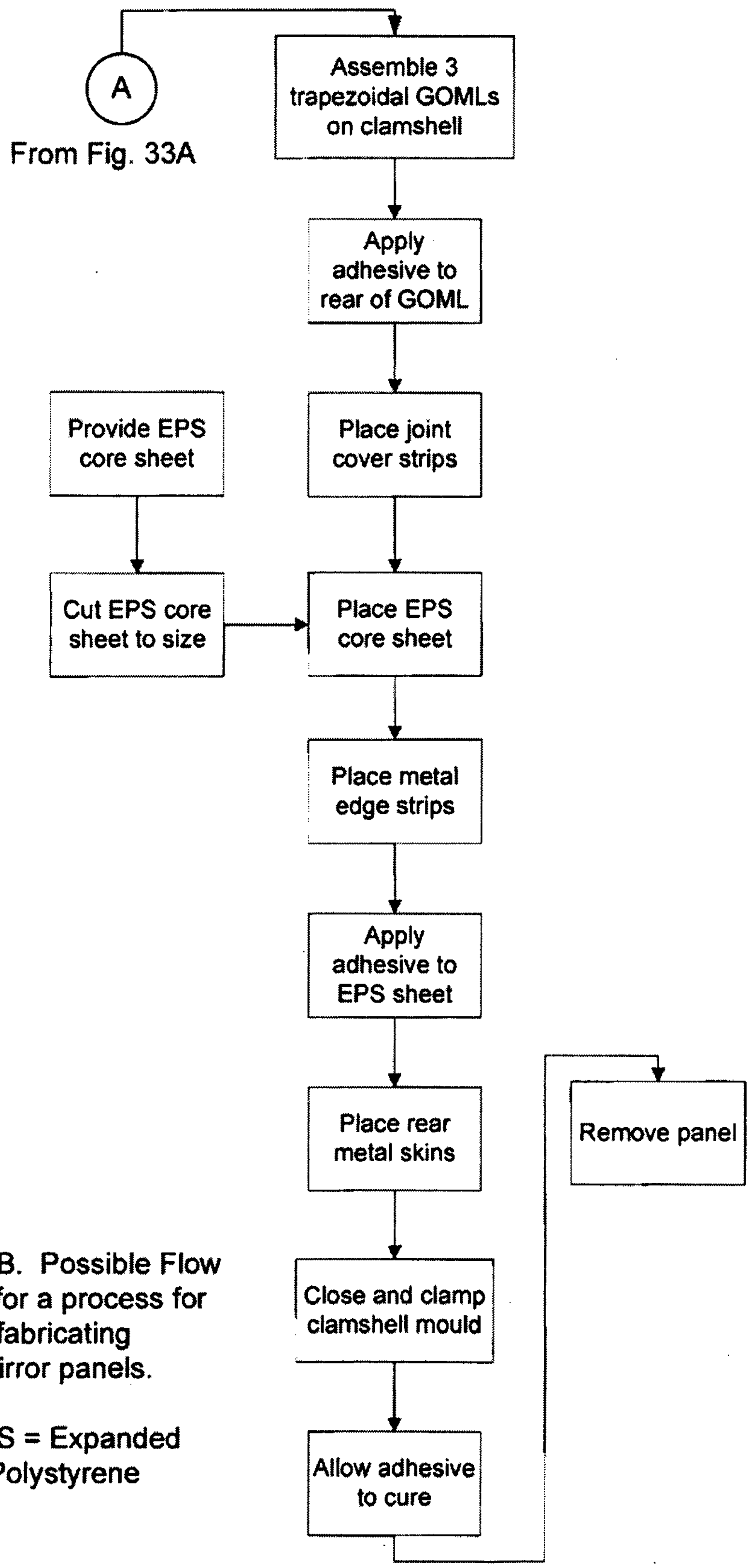

Fig. 33B. Possible Flow chart for a process for fabricating mirror panels.

*EPS = Expanded Polystyrene

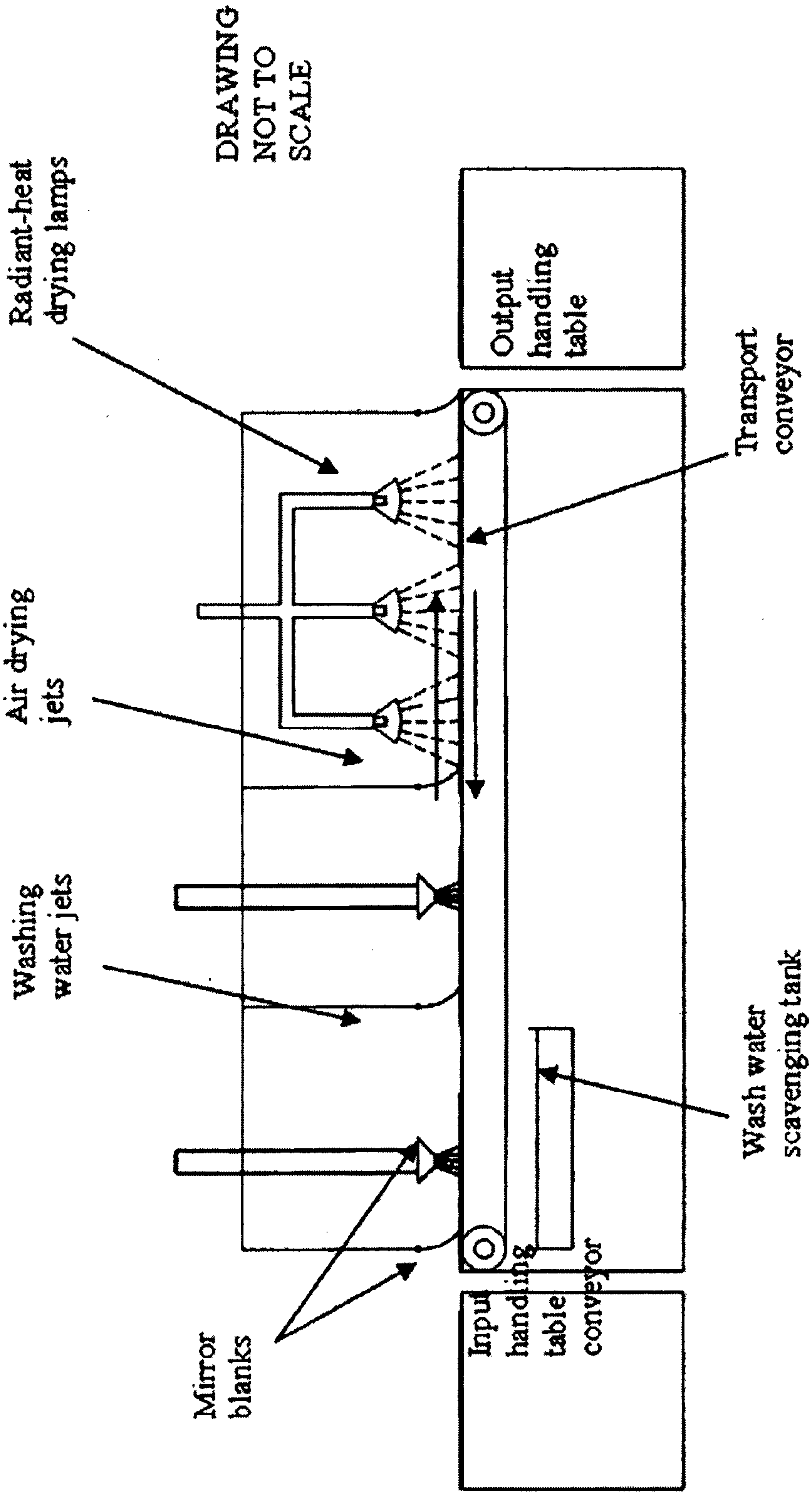

Figure 34. Schematic of mirror cleaning tunnel.

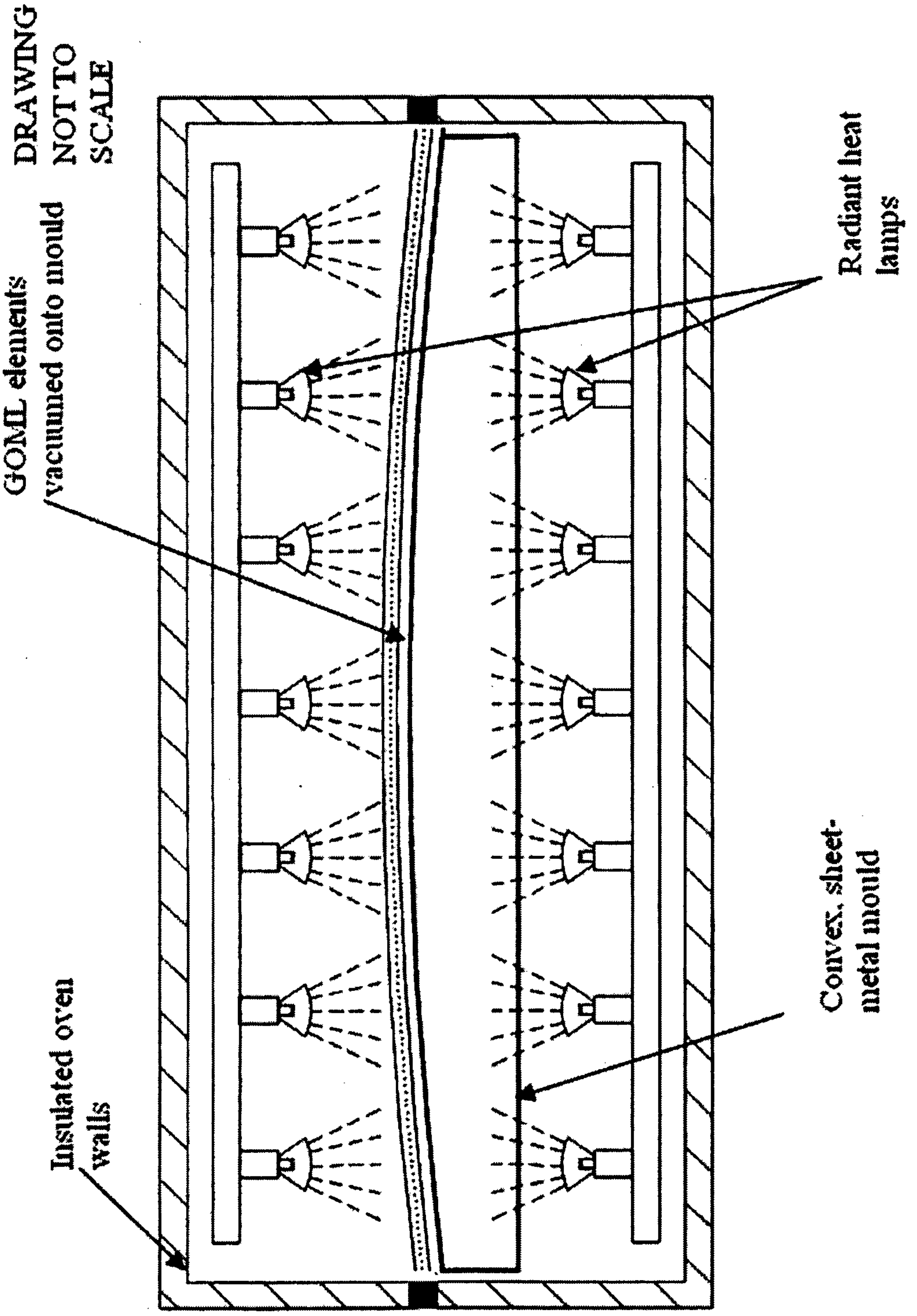

Figure 35. Radiant heat oven for laminating glass-on-metal-laminate elements.

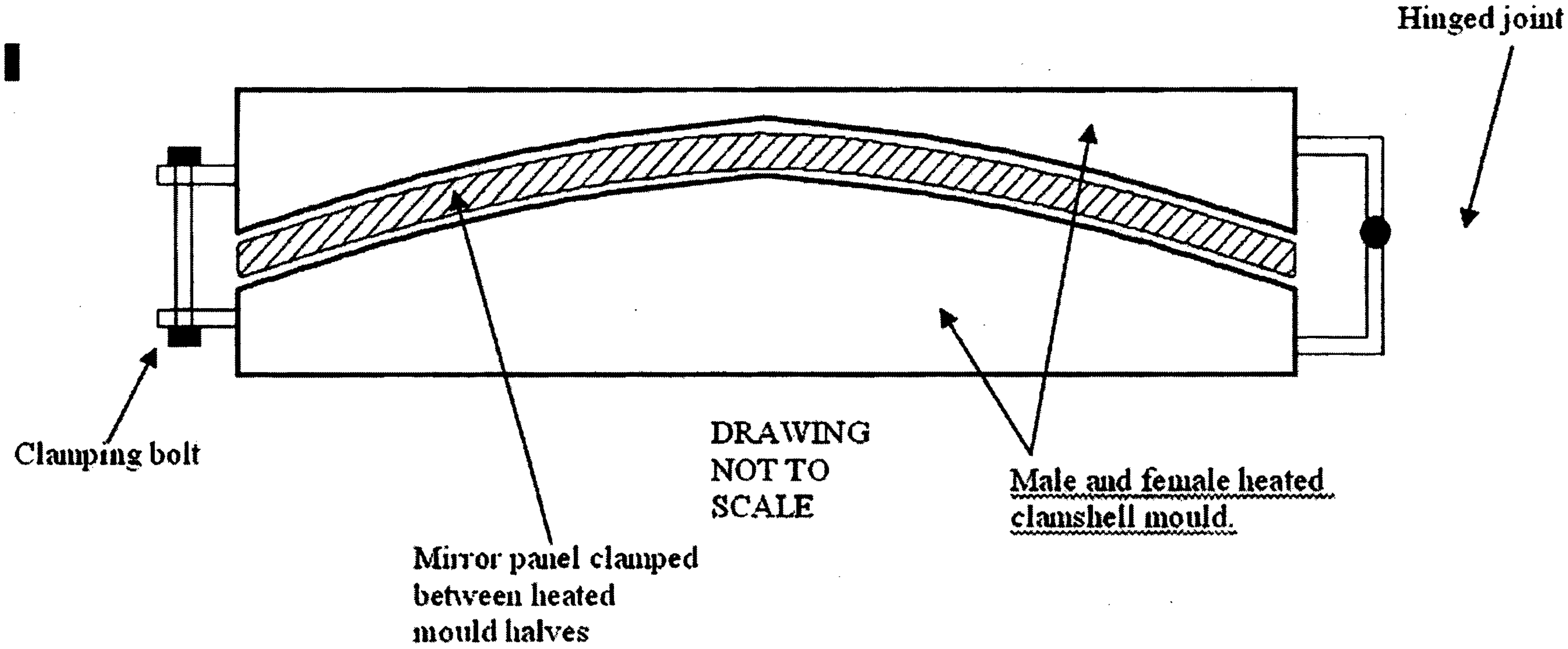

Figure 36. Heated clamshell mould for panel fabrication.

INTERNATIONAL SEARCH REPORT

International application No.
PCT/AU2011/001104

A. CLASSIFICATION OF SUBJECT MATTER

Int. Cl.

F24J 2/10 (2006.01) ***G02B 5/10*** (2006.01)

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
WPI, EPDOC with class marks; F24J 2/low, B32B1/low, B32B7/10/low, B32B9/04/low, B32B17/06/low, C03C27/10, G02B5/10 and keywords (mirror, reflect, metal+, +steel+, ss, aluminium+, aluminium+, adhesive?, gel, bond+, stick+, adhere, EVA, vinyl acetate?, glue+, cement+, join+, curv+, concav+, convex+, bend+, bent+, wave+, undulate+, inclin+, slope+, core+, fill+, +styrene?, honeycomb?, +board?, corrugated+, plastic? , polymer+, sandwich+ , layer+, lamina+, cellul+, solar+ or sun+, mould+ or mold+).
GOOGLE ADVANCED PATENT SEARCH, USPTO and ESPACENET with above keywords.

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
P, X	WO 2010/115237 A1 (WIZARD POWER PTY LTD [AU]) 14 October 2010 Figure 1, from page 6, line 30 to page 8, line 11 and page 9, lines 24 – 32	1 – 11, 13
X	US 4465734 A (LAROCHE et al.) 14 August 1984 Figures 2 & 3, Column 6, lines 9 – 65 and claims 1 - 25	2 – 14

[X] Further documents are listed in the continuation of Box C [X] See patent family annex

* Special categories of cited documents:

- "A" document defining the general state of the art which is not considered to be of particular relevance
- "E" earlier application or patent but published on or after the international filing date
- "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
- "O" document referring to an oral disclosure, use, exhibition or other means
- "P" document published prior to the international filing date but later than the priority date claimed
- "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
- "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
- "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
- "&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
30 September 2011	07/10/2011

Name and mailing address of the ISA/AU	Authorized officer
AUSTRALIAN PATENT OFFICE PO BOX 200, WODEN ACT 2606, AUSTRALIA E-mail address: pct@ipaustralia.gov.au Facsimile No. +61 2 6283 7999	**KOSALA GUNATILLAKA** AUSTRALIAN PATENT OFFICE (ISO 9001 Quality Certified Service) Telephone No : +61 2 6222 3652

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 7077532 B1 (DIVER Jr. et al.) 18 July 2006 Whole document	
A	US 4124277 A (STANG) 07 November 1978 Whole document	

This Annex lists the known "A" publication level patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

Patent Document Cited in Search Report		Patent Family Member					
WO	2010115237	NONE					
US	4465734	BE	893050	DE	3216844	ES	265557U
		ES	8306688	FR	2511775	GB	2104444
		JP	58035360				
US	7077532	NONE					
US	4124277	NONE					

Due to data integration issues this family listing may not include 10 digit Australian applications filed since May 2001.

END OF ANNEX