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CONTRACTOR REPORT

Design and Development of a Laminated Glass-Plastic Fresnel Lens for Point Focus Photovoltaic Systems

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DISCLAIMER

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Abstract

The design and development of a laminated glass-plastic Fresnel lens for point focus photovoltaic systems use is described. The objective of this development was to examine the feasability of producing lenses with a cost effectiveness superior to that of lenses made by casting of acrylic. The procedure used in executing this development, the method used in cost effectiveness evaluation, results obtained and recommendations for further work are presented.

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INTRODUCTION

Fresnel lenses for photovoltaic applications are currently produced by either casting or compression molding acrylic plastic material. Although high optical qualities have been achieved by these methods, there are a number of construction features which might be improved. Improvement potentials include,

- o   Reduced cost

- o   Greater stiffness

- o   Improved abrasion resistance .

- o   Reduced thermal expansion and contraction

These opportunities for improvement of Fresnel lenses were recognized by RCA Laboratories who conceived and reduced to practice a laminated lens vacuum casting technique [1]. This work, covered under U.S. patent 4,170,616 formed the background for the study work reported herein. The objective of this development project was to further the task of establishing the feasability of producing lenses with a cost effectiveness superior to that of monolithic cast acrylic.

The low cost Fresnel lens concept is based upon the use of a glass plate to which are affixed plastic facets comprising the refracting elements of a plano-convex lens. With this arrangement the glass provides the stiffness, abrasion resistance and low thermal expansion and contraction characteristics. The plastic facets bonded to the glass surface face the target. These facets are reasonably protected from the environment.

The development aspects of this concept deal with the selection of suitable plastic faceting materials, the identification of appropriate manufacturing methods, the verification of environmental resistance, the determination of optical characteristics of the design and the measurement of cost effectiveness of the selected arrangements.

The optical design of the Fresnel lens used in this study was developed in a parallel project conducted by Swedlow, Inc.[2]. The design consisted of 6.7 inch square lens elements arranged in a 5 x 5 parquet. See Figure 1 and Table 1. Since the indices of refraction of the materials studied were different from that of acrylic, the optical design was not optimal for these materials. The non-optimal design was, however, deemed to be satisfactory for the purpose of demonstrating the capabilities of the study materials.

Replicating tools developed in this parallel project were used in the subject study to generate the plastic faceting as applied to the glass superstrate.

1

Slab Thickness

Total Thickness

VIEW B

.125 Glass

6.70

6.70

7.37

.61 x .61

ρ

R

δ

R

Ø

VIEW A
FACET DETAIL
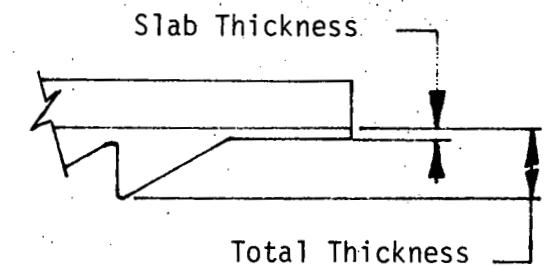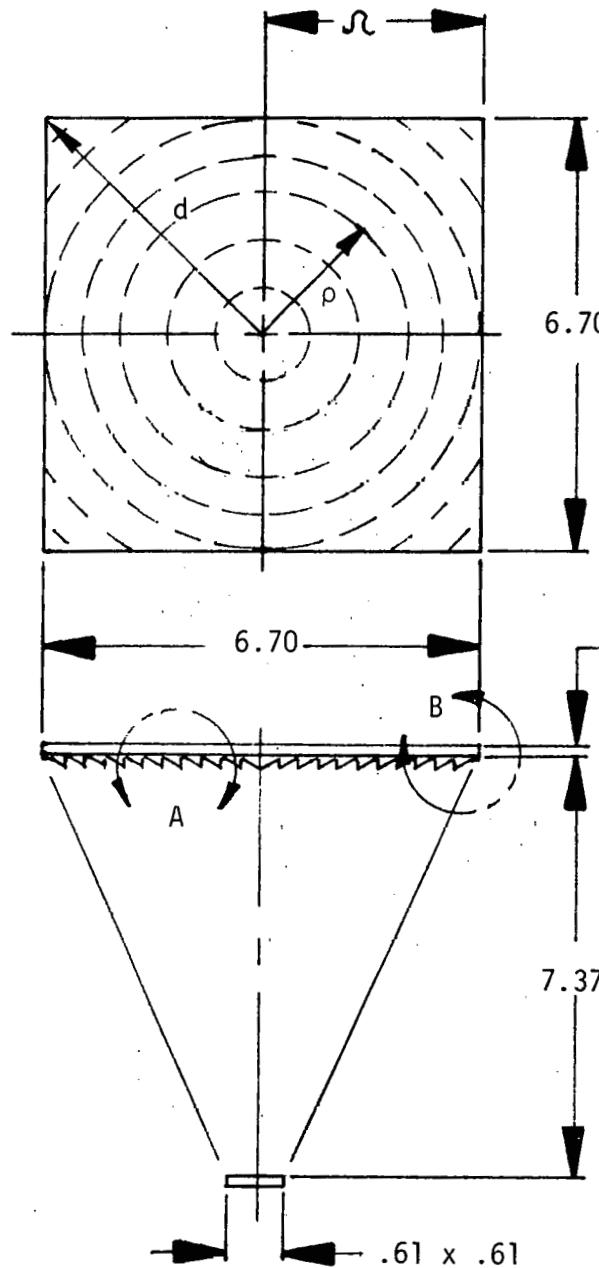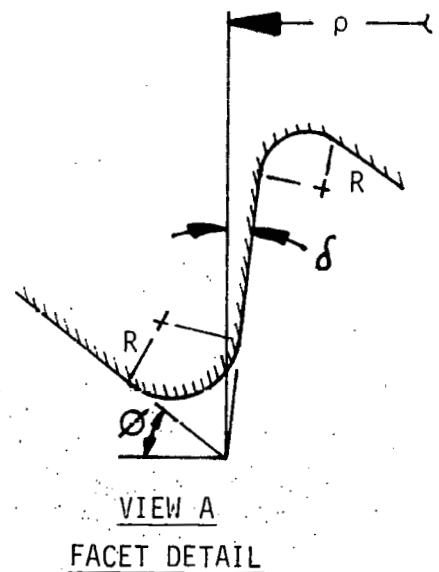
LENS ELEMENT GEOMETRY
FIGURE 1

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TABLE I

CHARACTERISTICS OF LENS

Solar spectrum of interest	λ_j	.4	μm – 1.1 μm
Width of facets (tip to tip)	w	.025	inch
Facet draft angle	δ	1.5	deg.
Index of refraction	η_D	1.486	
Lens-to-target distance	F	7.37	inch
Facet tip and root radii	R	.0001	inch
Lens element half width	r	3.35	inch
Lens element half diagonal	d	4.74	inch
Parquet		5 x 5	elements
Parquet dimension		34.5	inch x 34.5 inch
Facet angle tolerance	$\Delta \phi$	± 1	mr

This geometry results in a blockage of solar ray transmission directed to the target of approximately 3.5%.

Total lens area	44.89 in^2
Horizontal area of tip & root radii	.86 in^2
Horizontal area of draft surface	.68 in^2
Total blockage area	1.54 in^2
Percent Blockage = 1.54/44.89 =	3.44%

EFFECT OF OPTICAL EFFICIENCY ON SYSTEM COST EFFECTIVENESS

To evaluate the cost effectiveness of alternative solar energy concentrating optical elements it is necessary to consider the affect of optical efficiency on system cost. The baseline optical element for this comparative analysis is the cast acrylic Fresnel lens. These lenses have been estimated to cost about $2.50 per square foot in 1978 dollars when production levels of a million square per year are reached [5]. Optical efficiency of these lenses are reported to be about 80% when evaluated over the silicon solar cell activation energy spectrum [2]. Clearly, if alternative lenses can be produced with comparable optical efficiencies and at a reduced lifetime cost then all is well. However, if alternative lenses are found to have lower optical efficiencies then a larger concentrator system is required in order to achieve an equal power output and costs will tend to substantially increase unless the optical element cost reduction can act as an offset.

The photovoltaic system power output per unit aperture area when using solar conentration is given by,

$$W/A = I_o \, \eta_B \, \eta_T \, \eta_I \, \eta_C$$

where,

$$W = \text{Total power output}$$

$$A = \text{Optical aperature area}$$

$$I_o = \text{Insolation}$$

$$\eta_B = \text{Transparent area efficiency}$$
$$\text{(Considers support structure optical blockage)}$$

$$\eta_T = \text{Lens transmission efficiency}$$

$$\eta_I = \text{Target intercept efficiency}$$

$$\eta_C = \text{Solar cell conversion efficiency}$$

All of the efficiencies, with the exception of the cell conversion efficiency, may be lumped together for this analysis and termed the optical efficiency.

$$\eta_o = \eta_B \, \eta_T \, \eta_I$$

It is apparent that the required aperture area is inversely proportional to this optical efficiency. In comparing optical systems, given that the power output, insolation and cell conversion efficiency are held constant, the ratio of area is equal to the ratio of optical efficiencies.

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$$A = \frac{1}{\eta_o} \cdot \frac{W}{I_o \eta_c}$$

$$A_2 = A_1 \frac{\eta_{o_1}}{\eta_{o_2}}$$

The system cost is, of course, directly proportional to the required optical aperture. System cost is generally comprised of the costs for concentration optics, silicon solar cell and assembly, array structure and tracking, assembly and testing.

$$C = C_o + C_s$$

where,

C = Total system cost

C_o = Concentration optics cost

C_s = All other system costs

Thus, for two competing systems their cost and efficiencies are directly related.

$$C_2 = C_1 \frac{\eta_{o_1}}{\eta_{o_2}}$$

For analysis purposes, it is assumed that only the concentration optics cost is variable. The relationship between the concentration optics cost and the optical efficiency for alternative systems may be derived based on the equality of total system costs.

$$C_1 = C_{o_1} + C_{s_1}$$

$$C_2 = C_1 \frac{\eta_{o_1}}{\eta_{o_2}} = C_{o_2} \cdot \frac{\eta_{o_1}}{\eta_{o_2}} + C_{s_1} \cdot \frac{\eta_{o_1}}{\eta_{o_2}}$$

$$C_{o_2} = C_{o_1} - \Delta C_o$$

where,

ΔC_o = The change in concentration optics cost between systems

For $C_2 = C_1$ then,

$$\frac{\eta_{o_1}}{\eta_{o_2}} (C_{o_1} + C_{s_1}) - \frac{\eta_{o_1}}{\eta_{o_2}} \Delta C_o = C_{o_1} + C_{s_1}$$

$$\Delta C_o = (C_{o_1} + C_{s_1}) \frac{\eta_{o_1} - \eta_{o_2}}{\eta_{o_1}}$$

Estimates of the photovoltaic concentrator system costs reveal that the concentration optics comprise about 25% of the total system costs[6]. Based on this it may be seen that a drop in optical efficiency for an alternative system of 10% requires a 40% drop in concentration optics cost in order to maintain an equality of total system cost.

$\frac{C_{o_2}}{C}$
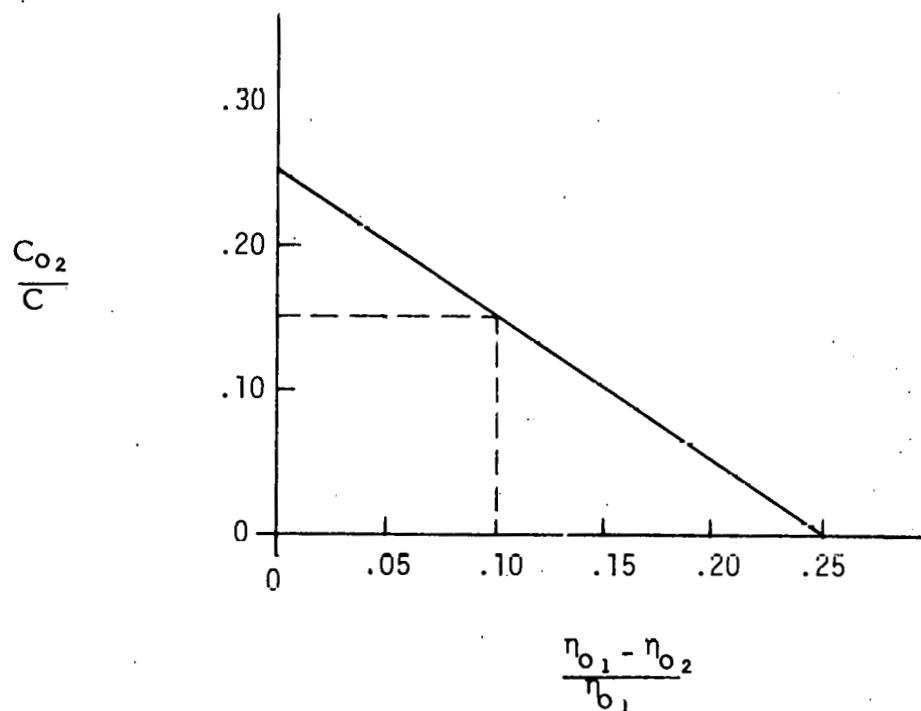
CONCENTRATOR SYSTEM COSTS VS LENS EFFICIENCY

FIGURE 2

Thus, relative optical efficiency is an important consideration in the evaluation of alternative optical elements in solar concentrators. Of course, the analysis just described assumes equal product lives.

GLASS SELECTION

The criteria which must be considered when selecting the glass superstrate include,

o   Resistance to thermal cycling stresses when bonded to plastic lens elements. Temperature extremes are from -22°F to +122°F.

o   Resistance to the impact of a 1.0 inch diameter hail impact at 55 mph velocity.

o   Light transmission in the wavelength range from 0.4 microns to 1.1 microns.

o   Minimum deflection when subjected to 30 mph wind loading.

o   Survival under a 90 mph wind loading.

o   Minimum cost.

Four types of glass were considered; ordinary soda lime, low iron soda lime, borosilicate and aluminosilicate. Ordinary soda lime glass is the most common, is low cost, and is readily available. The problem with this glass is that it contains iron which limits its transmission of solar energy. Low iron soda lime glass offers an alternative. Schott Glass Co. of Germany produces a B-270 iron free crown glass which has excellent light transmission but is very expensive. A source of inexpensive low iron glass is Jeannette Corporation, 106 Sailer Street, Jeannette, PA. 15644, 412-523-8501, Solaclean Type A or B. These glasses are much lower in cost than Schott B-270. Transmission is down about 2%. AFG also produces a low iron soda lime called Solatex but this glass has a textured surface which renders it unsuitable for this application. Borosilicate glass also has excellent light transmission but only Corning Glass Works produces a material suitable for solar application and availability is poor while the cost is high. The best type of glass, sodium aluminosilicate, is the least available for solar applications and is about as expensive as the borosilicate.

Cost and light transmission data obtained for these glasses are shown in Table II.

TABLE II

COST AND LIGHT TRANSMITTANCE DATA

FOR

CANDIDATE GLASS TYPES

Glass Type	Trade Name	Manufacturer	Average Percentage Light Transmission in Wavelength Range 400 mm to 1100 mm For 3/16" glass	January, 1980 Prices For Truckload Quantities, $/ft^2 Thickness, inches				
				1/8	5/32	3/16	7/32	1/4
Soda-Lime, Tempered	Soda-Lime, Tempered	Guardian Glass	82	0.65	0.68	0.80		1.10
Soda-Lime, Untempered	Soda-Lime	PPG	82	0.48		0.84		0.88
Low-Iron Soda-Lime, Tempered	Solatex	AFG	89	0.61	0.72			0.83
Borosilicate	Pyrex	Corning Glass	92	2.00			4.25	
Iron-free Crown glass, Polished, Untempered	B-270	Schott Optical Glass	92			19.70[1]		
Low-Iron Soda-Lime	Solaclear Type A Type B	Jeannette	80 89	1.16 .91				

(1) It has been reported that this glass may be obtained for about $1.78/ft^2 in large quantities.

Based just on the cost and availability factors, the only viable glass type which can be currently considered is the soda lime type.

Hail impact testing was conducted on tempered soda lime glass and acrylic as a part of this project[3]. Under multiple impacts of a 1.0 inch diameter hail stone, the velocity at which the glass and acrylic would fail was determined. Results are,

	Material (1/8" thick)		Failure Velocity
Acrylic			150 ft/sec (102 mph)
Tempered Soda Line Glass			110 ft/sec (75 mph)

Both of these materials were found to survive the specified 55 mph hail impact condition.

The modulus of elasticity of glass is 1×10^7 psi whereas acrylic is 0.45×10^6, thus glass is over 20 times stiffer in bending than acrylic of equal dimensions. Fresnel lenses made of acrylic and used in solar applications have normally been about 1/8 inch to 3/16 inch thick. The use of 1/8 inch thick glass with about 10 to 20 times the stiffness of existing lenses therefore, seems appropriate.

The maximum stress and deflection of a 1/8 inch thick glass 34.5 inches by 34.5 inches square are shown in Figure 3 as a function of wind velocity for the case where the wind is acting normal to the plate. Small deflection theory is used and as such, for wind conditions above 30 mph the stresses are approximately correct but the deflection is greater than would actually occur.
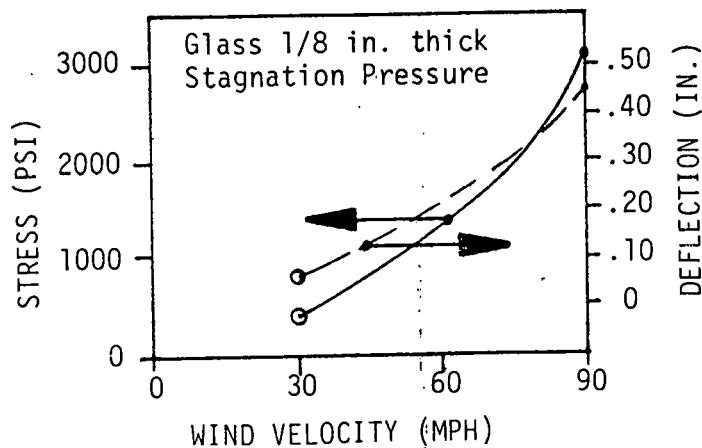
**GLASS STRESSES AND DEFLECTION VS NORMAL WIND VELOCITY
FOR A 34.5 INCHES SQUARE PLATE
FIGURE 3**

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Based on a glass ultimate strength of 10,000 psi under short term or momentary loading it is estimated that a periodic loading, such as developed by wind, would result in an allowable strength of about 3,000 psi. This allowable is very close to the expected stress under worst case wind conditions. Thus, it appears that the 1/8 inch thick glass is structurally appropriate.

The glass used in this study was 1/8 inch thick soda lime and although the light transmittance is not as high as one would like its cost and availability are appropriate in the near term.

FACET MATERIAL SELECTION CONSIDERATIONS

Selection of the proper facet material involves optical, mechanical, process and cost considerations in addition to providing for environmental survivability. These points of design concern will be briefly described prior to the presentation of study results.

Maximizing specular transmission of solar radiation to the photovoltaic target is fundamental to lens design. High lens transmission results in the need for less concentrators and, thus, reduced system cost. The transmission within the selected radiation band must be high and specular. Outside this pass band the attenuation should be high in order to minimize radiant heating of the photovoltaic device. Stability of the optical focus is dependent upon changes in index of refraction due to temperature and stress variations. Minimizing these effects is desirable. To maximize the optical concentration it is also desirable to obtain a material with the minimum variation in index of refraction with wavelength. Additionally, to maintain this specular transmission the lens material must be environmentally stable. Effects on optical properties of the lens material should be minimally affected by hydrolysis and oxidation mechanisms and resistant to ultra-violet radiation deterioration.

Dissimilar coefficients of expansion will exist between the facet material and the glass superstrate. As such, adhesion of the facets to the glass, stress induced deformations of the weaker facet material and general bending of the lens may result in mechanical failures and/or reduced optical performance. The modulus of elasticity of the facet material, the thickness of this plastic, its coefficient of thermal expansion and its ability to adhere to the glass are important variables in this material selection.

The selected process for applying the facet material to the glass must result in a void and inclusion free faceting while producing a high quality replication of the lens mold surface. Shrinkage of the plastic material during cure, if present, should be minimized. And, of course, the process must be low cost in the production volumes anticipated for solar concentrators.

Functionally the lens facets must not optically degrade over a life of some 20 years when exposed to the imposed stresses of its environment. Moisture's effect on the bond of facets to the glass is of critical concern. Also, the changes in optical properties such as coloration, becoming diffuse in optical transmission, and changes in geometry must be obviated.

These concerns, therefore, constitute the background against which alternative materials are to be judged with respect to suitability as a facet material in this solar concentration application. It was not possible within the scope of this program to quantify all of these characteristics for competing materials. These characteristics were, however, used as subjective criteria in defining reasonable material candidates.

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FACET MATERIAL SELECTION

Five general criteria were used to judge the general suitability of polymers for facet material consideration. These criteria included,

   o   Solar energy transparency

   o   Flexability or extensional stiffness

   o   Weatherability

   o   Processability

   u   Price

Only those polymeric materials which were currently transparent, as opposed to those materials which could potentially be made transparent, were considered for evaluation.

Flexible plastics were assumed to be the preferred material when bonding to glass. This assumption was based on the consideration of the mismatch in coefficients of thermal expansion and the effect of this mismatch on material and bond joint survivability. The difference in coefficients is about one order of magnitude and can result in significant bond shear stresses and polymer deformations which are cyclic in nature. For screening purposes, the material hardness range of 30 to 70 Shore A was selected while the tensile modulus of elasticity range of 100 to 1800 psi was assumed.

Only material types which possessed an acceptable combination of properties such as ultra-violet light stability, oxygen and ozone resistance, and moisture resistance were considered. A judgment was made as to the expected life of these materials relative to the life of as-cast acrylic. This factor is important in relative cost considerations.

Processability of materials was not initially used in the material selection screening. Materials which were capable of being injection molded would be preferred in a long term sense. However, for this lab study, material which would be readily fabricated via casting techniques were chosen.

Material candidates were not initially screened out on the basis of price due to the small quantity of material which would be used for the facets. Certain materials, however, are of substantial price and coupled with processing costs may result in their exclusion.

The general selection of candidate polymeric material types was based on the screening noted above. This screening is summarized in Table III and reflects the passing of thermoplastics, thermosets, and elastomers through progresive screens of transparency, flexibility and weatherability.

TABLE III

MATERIAL GENERAL SCREENING

MATERIAL	TRANSPARENCY	FLEXIBILITY	WEATHERABILITY
Acrylics Acrylics, Modified Cellulosics Fluorocarbons Ionomers Nylons Polycarbonates Polyesters Polyethers, Chlorinated Polyimides Polyolefins Polyphenylene Oxides Polystyrenes Polysulfones Vinyls, Modified	Acrylics Acrylics, Modified Cellulosics Fluorocarbons Ionomers Nylons Polycarbonates Polyesters Polyolefins Polystyrenes Polysulfones Vinyls, Modified	Acrylics, Modified Polyolefins Vinyls, Modified	Acrylics, Modified Polyolefins Vinyls, Modified

ELASTOMERS
 	
Acrylates
Butyls
Chloroprene
Fluorocarbons
Nitriles
Polyester, Thermo-
        plastic
Polyethylene,
   Chlorosulfonated
Polyolefins
Polysulfides
Polyurethanes
Silicones
Styrene-Butadiene
	Acrylates
	Butyls
	Chloroprene
	
	Fluorocarbons
	
	Nitriles
	Polyolefins
	Polyurethanes
	Silicones
	Sturene-butadiene
		Acrylates
		Butyls
		Chloroprene
		
		Nitriles
		Polyolefins
		Polyurethanes
		Silicones
		Styrene-butadiene
			Acrylates
			
			Butyls
			
			Polyolefins
			Polyurethanes
			Silicones

THERMOSETS Acrylics, Modified Alkyds Diallyl Phthalates Epoxies, Modified Furans Melamines Phenolics Polyesters Silicones, Rigid Resins	Acrylics, Modified Epoxies, Modified Phenolics Polyesters Silicones, Rigid Resins	Acrylics, Modified Epoxies, Modified Polyesters	Acrylics, Modified Epoxies, Modified

Material family candidates which were included in further analysis, based on this screening, may be seen in Table IV.

TABLE IV

GENERAL CANDIDATES

Thermoplastics

        Acrylics - Modified

        Olefins

        Vinyls - Modified

Thermosets

        Acrylics - Modified

        Epoxies - Modified

Elastomers

        Acrylates

        Butyls

        Olefins

        Silicones

        Urethanes

Manufacturers and suppliers were contacted in order to obtain recommendations of transparent, flexible, and weatherable candidates within each material category. Due to budget constraints the evaluation was restricted to liquid castable resins only. Certainly, the other materials would warrant evaluation if the outcome of the general evaluation of the concept should prove favorable.

The material categories which were selected for experimentation were, therefore; modified epoxies, silicones, and urethanes. Seven resin systems were obtained for initial screening. These are set forth in Table V.

TABLE V
CANDIDATE MATERIAL FOR EVALUATION

Trade Name	Manufacturer/Supplier	Material Category	Material Type
ND-1100	Cal Polymers	Thermoset Urethane	Aliphatic Polyether
Urelane 5754A/B	M & T Chemicals	Thermoset Urethane	Aliphatic Polyether
SS-6640	Swedlow	Thermoplastic Urethane	Proprietary
RTV-670	General Electric	Thermoset Silicone	Dimethylsiloxane
SS-5272Y(HT)	Swedlow	Thermoset Silicone	Proprietary
DER 332/732	Dow Chemical	Thermoset Epoxy	Modified diglycidyl ether of bisphenol A
ERL-4221/NIAX Polyol LHT-240	Union Carbide	Thermoset Epoxy	Cycloaliphatic

These materials were cast onto soda lime plate glass in thin sections and compared in terms of ease of casting, appearance, thermal cycling stability, and adhesion to the glass. The thermal cycling test consisted of ten cycles between -40°F and +140°F. A summary of the results of this evaluation is shown in Table VI.

TABLE VI
CANDIDATE MATERIALS
COMPARISON OF CASTINGS ON GLASS

Trade Name	Ease of Casting	Appearance	Thermal Cycling Stability	Adhesion to Glass
ND-1100	Good	Water-white	Fair	Good
Urelane 5754A/B	Poor	Water-white Many bubbles	Good	Good
SS-6640	Good	Water-white, few bubbles, tacky surface	Good	Good
RTV-670	Good	Water-white	Good	Poor
SS-5272Y(HT)	Good	Water-white	Good	Good
DER 332/732	Good	Yellow	Poor	Good
ERL-4221/NIAX Polyol LHT-240	Good	Light Yellow	Poor	Good

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ND1100 had good optical qualities and adhered well to glass. Urelane 5754 had a very short pot life which did not allow for adequate degassing: castings made from it had many bubbles. SS-6640 had a few bubbles, a tacky surface, and adhered well to glass. Both the silicones were cast using different primers. RTV-670 castings were easily pulled off the glass by hand; SS-5272Y(HT) adhered well both with and without primers. Both the epoxy castings had a yellow color but adhered well to glass. A thermal cycling test of ten cycles between -40°F and 140°F resulted in the low temperature cracking of DER 332/732 and the partial delamination of ERL-4221. The other candidates showned no apparent changes. As a result of this analysis, both epoxy candidates and Urelane 5754 were eliminated from further consideration.

The materials which then remained in the evaluation were samples of urethanes and silicone.

TABLE VII

CANDIDATE MATERIALS

Trade Name	Manufacturer/Supplier	Class
ND 1100	Cal Polymers	Thermoset Urethane
SS-6640	Swedlow	Thermoplastic Urethane
RTV-670	General Electric	Thermoset Silicone
SS-5272Y(HT)	Swedlow	Thermoset Silicone

Cal Polymers urethanes are room-temperature cured, two-part systems. ND 1100 partially delaminated from the glass when subjected to a thermal cycling of 10 cycles between -40°F and 140°F; as such, a more flexible Cal Polymers urethane with a hardness closer to that of silicones was selected for laminated lens process development work. Adhesion to glass was fairly good, although the urethane could be pulled off the glass by hand with some effort.

The SS-6640 candidate, also a urethane, is press-cured at elevated temperature. It has a very short pot life which makes bubble removal a problem. The primary difficulty with this material is that it partially adheres to the flexible molds which were used. This material was dropped from further consideration due to these problems and budget constraints.

The adhesion of RTV-670, a silicone, to glass is not as good as ND 2300 even with the use of the various primers.

SS-5272Y(HT) is a heat-cured silicone with excellent adhesion to glass. It did, however, present difficulties in terms of release from a flexible mold and bubble removal due to its very high viscosity (3000 poise). The flexible molds tried included RTV-664, RTV-60, the silicone itself used as a mold, and polypropylene.

The costs of these candidate materials including the SS-6640, is shown in Table VIII and IX.

TABLE VIII

RESIN PRICES

Candidate	Price, $/lb as of December 1979	Density Lb/Gal.	Price, $/Gal.
ND 2300	3.50	8.0	28.0
SS-6640	1.50	8.0	12.0
RTV-670	14.00	7.9	110.6
SS-5272Y(HT)	17.40	8.0	139.2

TABLE IX

RESIN COST AS A FUNCTION OF SLAB THICKNESS[1]

Resin Slab Thickness, Mils	Volume of Facets and Slab, In^3/ft^2	Resin Cost, $/ft^2$ Candidate			
		ND2300	SS-6640	RTV-670	SS5272Y(HT)
0	0.98	0.12	0.05	0.47	0.60
20	3.87	0.47	0.20	1.84	2.34
40	6.76	0.82	0.35	3.21	4.09
60	9.65	1.17	0.50	4.58	5.84
80	12.54	1.52	0.65	5.95	7.59
100	15.43	1.87	0.80	7.32	9.34

(1)See Figure 1 for a description of slab thickness

Testing of the three remaining candidate materials were conducted and the results of that testing are reported in the following sections of this report.

GENERAL TESTING

A series of tests were performed on fabricated single lenses. The objective of these tests was to define the relative performance of the candidate materials both before and after weathering and to rank candidates on the basis of weatherability. The following tests were done on single lenses and plane sections:

- o   Accelerated UV-Aging

- o   Water Absorption

- o   Weatherometer

- o   Optical Performance

- o   Light Transmittance and Haze

- o   Peel Strength

- o   Thermal Cycling

- o   Hail Impact

The optical performances of the lenses and the light transmittance, haze, and peel strengths of the plane sections were determined before and after the accelerated UV-aging, water absorption, and weatherometer tests. The thermal cycling test was done on lenses; the hail impact test was done on array-size tempered glass only.

The following polymer candidates were tested:

Trade Name	Class
RTV-670	Thermoset Silicone
SS-5272Y(HT)	Thermoset Silicone
ND-2300	Thermoset Urethane

Results of this testing are reported in Reference 3 and highlights of this testing are presented below.

Accelerated UV-Aging

The accelerated UV aging tests were conducted using a UV tower designed by E.I. DuPont de Nemours & Company. This apparatus serves as a tool for obtaining rapid evaluations of the relative instabilities of polymer materials upon exposure to UV light. The UV tower approximates natural solar energy in the ultraviolet region of the spectrum below wavelengths of 360 millimicrons. The illumination peaks at 320

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millimicrons with an intensity which is about three times that of natural noon sunlight in June. Radiation in the UV tower comes from eight 20-watt fluorescent vertically-mounted sunlamps.

The exposure period was 336 hours. DuPont found that in their use of the UV tower on specific materials, 336 hours of exposure is equivalent to approximately five years of exposure in the Florida sun. Due to known variations in correlations of artificial exposure to solar exposure with various materials, the equivalency is a rough approximation at best.

Of the silicone candidates, only one SS-5272Y(HT) specimen exhibited a slight haze after the two-week UV tower exposure. RTV-670 specimens were unchanged. All of the ND-2300 specimens turned amber and became very sticky, apparently not stable under these test conditions.

Water Absorption

Water absorption tests were conducted in accordance with ASTM Standard Method D570-63. Specimens were dried in an oven for 24 hours at 50°C, cooled in a desiccator, and immediately weighed. These conditioned specimens were then placed in a container of distilled water maintained at 23°C, resting on edge, in order to determine the total water absorbed when substantially saturated.

After 24 hours, the specimens were removed from the water, all surface water wiped off with a dry cloth, weighed immediately, and then replaced in the water. The weighings were repeated at the end of the first week and every two weeks thereafter until the increase in weight per two-week period, as shown by three consecutive weighings, averaged less than one percent of the total increase in weight, or 5 mg, whichever was greater. The specimens were then considered to be substantially saturated. The difference between the substantially saturated weight and the dry weight was considered as the water absorbed.

The average weight percent of water absorbed and soluble matter lost based on the specimen weights are as follows:

Candidate	Wt. % Water Absorbed	Wt. % Soluble Matter Lost
Monolithic Acrylic	1.49	0.07
RTV-670	0.07	0.02
SS-5272Y(HT)	0.07	0.05
ND-2300	0.62	0.04

The acrylic lens did not change in appearance. One RTV-670 specimen was slightly hazy and yellow; two did not change. Two SS-5272Y(HT) specimens were hazy with one unchanged. Four of six ND-2300 specimens delaminated; the other two were unchanged. All candidates are apparently affected by the test conditions, RTV-670 being most stable.

Weatherometer

The weatherometer tests were conducted per Procedure A of ASTM D256-70. The effects of accelerated weathering on the specimens were determined using the following Atlas equipment: model 65/DMC-R weatherometer; model RM-5A conversion Xenon unit; model CS-5 Xenon ARC lamp cooling water circulator. The temperature was maintained at 63° ± 2°C. The cycle consisted of 102 minutes of light followed by 18 minutes of light combined with demineralized water spray. The power input to the xenon-ARC lamp was raised from 5000 watts to 7000 watts over a 1500 hour lamp life in order to provide a constant irradiance. The test specimens were exposed for 2000 hours.

All the ND-2300 specimens, both the 2:1 and 3:2 ingredients ratio, dissolved in the weatherometer and flowed off the glass within the first 1000 hours. All the silicone lenses survived the 2000 hours of testing without discoloration or loss of adhesion to glass. The monolithic acrylic lenses remained unchanged in appearance after the weatherometer exposure.

Optical Performance

Lens efficiencies and energy distributions across the target were obtained for the surviving lenses in the testing program. Of the ND-2300 lenses, the water absorption specimen delaminated in some areas resulting in a 39% lens efficiency after weathering. The weatherometer sample dissolved completely. The UV-aging specimen efficiency dropped from 64 to 56%. The silicone lens efficiencies change less than 6% for all weathering tests. Monolithic acrylic lens efficiencies showed increased efficiencies after weathering which cannot be explained. The efficiencies obtained from the lens analyzer are suspect due to variations up to 10% in the values of control specimens. The values for the most weatherable candidates, silicones, are therefore too close to rank on this basis.

Light Transmittance and Haze

Light transmittance and haze values for the candidate materials before and after weathering are shown in Reference 3. These results were then categorized in terms of unweathered and weathered specimens for each weathering test. The change in these values due to weathering were averaged for each candidate and shown with the data sheet.

Urethane ND-2300 samples dissolved in the UV-aging and weatherometer tests. The water absorption test sample experienced a drop of 1.7% in light transmittance and a 3.4% rise in haze. The average rise in light transmittance and drop in haze for SS-5272Y(HT) were 2.7 and 9.5% respectively. RTV-670 had values of 2.3 and 11.0%. The relatively high haze values of the silicones are due to lint and dust pickup. Silicones require a filtered environment in order to protect against this pickup. Transmittance values for all candidates are very close.

Peel Strength

Peel strengths were attempted for all specimens. The ND-2300 samples averaged 34 seconds per inch using a 1 1/2 pound weight. All silicone SS-5272Y(HT)

specimens failed cohesively at 6 1/2 pounds. RTV-670 was too brittle and broke in all cases upon the application of the slightest load. The material ranking in terms of adhesion to glass would be SS-5372Y(HT) (best), ND-2300 (middle), and RTV-670 (worst).

Thermal Cycling

The thermal cycling test consisted of 434 cycles between +120°F and -22°F. Cycle time was about 2 hours composed of 20 minute temperature transistions, 30 minute temperature stabilizations, and 5 minute minimum specimen temperature dwells at each temperature extreme. All six laminated lenses showed no evidence of blistering, peeling, cracking, discoloration, or other degradation after the test.

Hail Impact

The hail impact test was conducted on 1/8 inch soda lime tempered float glass panels 34 1/2 x 34 1/2 inches square. Hail stones were 1.0 inch in diameter. Terminal velocity of this size of hail stone is about 55 miles per hour and this was considered to be the minimum acceptable failure velocity. A range of velocities were tested, however. The 1/8 inch glass, the lowest caliper selected for impact testing, survived all shots and was therefore selected for use in the final single lens.

Material Candidate Selection

Table X contains a weatherability ranking of material candidates based on the results of the UV-aging, water absorption, weatherometer, and thermal cycling tests. Optical performance, light transmittance, haze, and peel strength test results are all reflected in the results of the other tests. The hail impact test results do not contribute to the weatherability ranking but merely dictate the glass thickness to use in final single lenses.

Rank factors of 1, 2, and 3 (low to high) were assigned to each candidate for each of the four tests. Each test was weighted according to its relative affect on life cycle performance. The product of a rank factor and a weight yielded a score for each test-candidate combination. The total weighted score for each candidate was then determined. Silicone candidates were very close and ranked almost twice as highly as the urethane candidate. RTV-670 is selected as the final candidate due to its much shorter cure cycle time and ease of processing.

TABLE X

MATERIAL CANDIDATES RANKING

TEST	CANDIDATE	RANK*	WEIGHT	SCORE		
				ND-2300	SS-5272Y(HT)	RTV-670
UV Aging	ND-2300	1	0.20	0.2		
	SS-5272Y(HT)	2	0.20		0.4	
	RTV-670	3	0.20			0.6
Water Absorption	ND-2300	1	0.20	0.2		
	SS-5272Y(HT)	3	0.20		0.6	
	RTV-670	3	0.20			0.6
Weatherometer	ND-2300	1	0.30	0.3		
	SS-5272Y(HT)	3	0.30		0.9	
	RTV-670	3	0.30			0.9
Thermal Cycling	ND-2300	3	0.30	0.9		
	SS-5272Y(HT)	3	0.30		0.9	
	RTV-670	3	0.30			0.9
				1.6	2.8	3.0

*Rank factors range from a low of 1 to a high of 3.

OPTICAL TESTING

The theoretical efficiency of this lens design, considering the wavelength range of .4 $\mu m \geq \lambda \geq 1.1$ μm, is estimated to be 83.5% excluding the effect of lens support losses.

o Combined reflection and absorbtion losses η_T .892

o Blockage due to facet root and peak radii and draft angle η_B .965

o Scattering losses due to surface roughness and diffraction η_S .980

o Target intercept losses η_I .990

$$\eta_o = \eta_T \eta_B \eta_S \eta_I = .835$$

When these individual lenses are assembled into a 5 x 5 parquet and peripheral support is provided the blockage losses due to this support are about 5.7% (η_{BS} = .943) resulting in an overall efficiency of 78.7%.

$$\eta = \eta_o \eta_{BS} = .787$$

Actual efficiencies would be expected to be lower than this due to manufactuing induced defects.

Testing of individual lens elements made of monolithic acrylic were conducted as a part of another contract (See Reference 2). The test methods used resulted in a considerable scatter in the measured efficiencies but it appears that the efficiency is about 80%. General results of that testing are shown below.

Test Agency	Test Method	Efficiency - η_o
Optical Science Group	Laser & Cell	.800/.855
Sandia	Sunlight & Cell	.810/.835
	Lens Analyzer	.726/.789
Swedlow	Lens Analyzer	.753/.801

The measurements of optical efficiencies of the glass-plastic lenses made as a part of this project used the Swedlow lens analyzer method. Data which was obtained was quite scattered and anomalies occured which could not be explained. The data is summarized in Table XI.

TABLE XI

OPTICAL EFFICIENCY TEST RESULTS

Facet Material (Soda Lime Glass Superstrate)	Original Sample	Weathered Sample	Water Exposed Sample	UV Exposed Sample
ND-2300	63.8	Fail		
	63.8	Fail		
	57.7	Fail		
	63.8		38.7	
	63.8			56.1
SS-5272	57.7	80.7		
	57.7		54.4	
	57.7			62.5
RTV-670	59.0	57.5		
	59.0	58.0		
	59.0		55.5	
	59.0			53.7
All Acrylic	68.5	77.1		
	60.4		60.4/68.0	

About the only things which can be concluded from this testing are that the glass plastic lenses had optical efficiencies approximately 10% less than monolithic acrylic and that water exposure of the urethane impairs the light transmission. These effects would be expected and the use of iron free glass, rather than the soda lime glass which was used, would greatly improve the transmittance of the composite lens.

LENS FABRICATION

Tooling options for casting polymeric facets on glass included: (1) nickel electroform; (2) flexible tools; (3) tooling design changes. Initial attempts at using a nickel electroform all resulted in failure to separate the casting from the tool without destroying the lens. This was due to the adhesion of the polymer to nickel and resulted in the two rigid substrates to be locked together by the intricate facet geometry. Release agents were not used as it was anticipated that this would create additional problems with reduced lens efficiency and tool cleaning labor. Certain flexible tools offered the mold-release characteristics required in urethane and sillicone castings as well as the flexibility needed to subsequently peel off the tool from the glass-polymer laminate. Both silicone and polypropylene molds were used as flexible tool candidates.

Potential tooling design changes for better release included: (1) shallower facets; (2) greater draft angle; (3) ejector pins. These options were not exercised due to project scope limitations.

Figure 4 depicts the process scheme developed for fabricating a glass-polymer laminated Fresnel lens. The glass surface was cleaned until a water-break free surface was attained, dried, flow-coated with the appropriate primer, and allowed to dry. The two-part resins were weighed out, mixed by hand to homogeneity, and then vacuum degassed to remove air entrained during mixing.
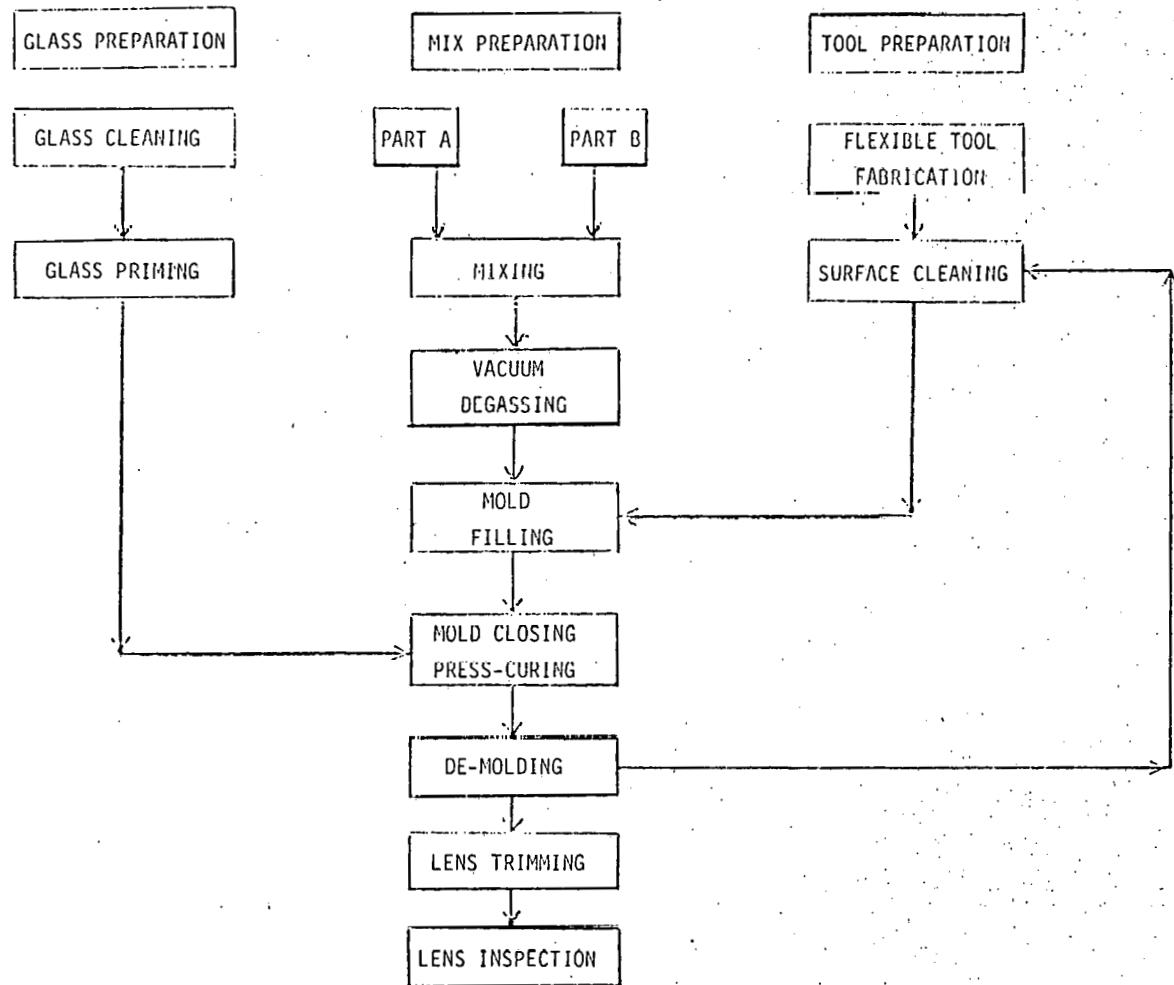
FIGURE 4

PRESS–CURED LAMINATED LENS PROCESS SCHEME

Silicone and polypropylene molds were made from nickel electroforms. Urethane candidates released from both tooling materials whereas silicones released from polypropylene only.

General Electric's silicone RTV-664, designed for urethane castings, is a room-temperature overnight-cured mold making material. Molds made from nickel electroforms had excellent facet definition.

Polypropylene molds were made by pressing heated polypropylene sheet onto a nickel electroform. The design parameters for maximizing the mold quality were as follows: forming temperature and pressure; cooling rate; de-mold temperature. The forming temperature was set at the 334°F crystalline melting temperature of polypropylene. A forming pressure of 400 psig was adequate. Too low a pressure yielded poorly-defined facets. Cooling rate affected the degree of warpage in the part as expected. Warpage was minimized by simply turning off the heat and allowing the part to cool by natural convection. A de-mold temperature of 260°F was selected. Too low a de-mold temperature resulted in facet deformation due to the different coefficients of thermal expansion of the nickel electroform and polypropylene. Higher de-mold temperatures proved impractical due to poly-propylene's drooping tendency and adhesion to nickel at these temperatures.

The degassed mix was then poured into the mold bordered by zinc chromate. Any bubbles entrained in the filled mold were removed by hand and/or vacuum degassed a second time. The primed glass was then placed edgewise onto the filled mold and slowly brought down until the mold was closed. The assembly was then placed in a press for curing at manufacturers' recommended cure times and temperatures. Very thin bubble-free castings were achievable by using the press. The project scope did not permit an optimization of each of these candidates in terms of cycle time and life cycle cost performance.

The time of application and magnitude of the cure-pressure were determined by trial-and-error. The press platens were in contact with the assembly at O psig until gelation occurred. Pressure was then raised to 2 psig to force out any air bubbles. After curing, the flexible mold was removed, and the casting was trimmed, cleaned, and inspected.

Each candidate had problems in processability. Urethanes ND-2300 and SS-6640 had very short pot lives which disallowed adequate degassing by this technique. Also, bubble-free castings were difficult to attain due to the adhesion of air bubbles between the mold facets. The problem might be solved by using automatic metering, mixing and degassed resin. This would be cost-effective at some production volume level.

Silicone SS-5272Y(HT), with a viscosity of 300 poise, required a few hours for all bubbles to egress from the filled mold. RTV-670 was relatively easy to process. Silicones would also benefit from automatic equipment.

The problem encountered with silicone molds used in a press was that the mold facets distorted under the load. All castings were made since then with polypropylene molds only. The release of urethane castings from polypropylene was not as easy as was with silicone molds.

Cure inhibition of silicones on new polypropylene molds was resolved by thorough solvent cleaning and repeated castings.

Candidate SS-6640 had to be dropped from further experimentation due to project limitations. It continued to have the problem of adherence to the flexible molds. All other candidates released from polypropylene without problems.

An effort was made to make castings as thin as possible in order to verify its feasibility. Facet-thin castings of both silicone and urethane candidates were made by pressing out the excess resin from the casting before gelation occurred. The urethane facets were pulled off the glass in some areas of the casting during the mold-release. A resin slab of 20-40 mils supporting the facets eliminated this problem. Silicone castings could be made facet-thin without this release problem.

CONCLUSIONS

Optical efficiency of the glass-plastic lens is largely dictated by the solar energy light transmittance of the glass superstrate which is used. Using common soda lime glass the efficiency is about 10% below that of an acrylic lens. If iron-free glass were available the efficiencies would be expected to be comparable, with the glass-plastic only a few percentage points lower.

The life expectancy of glass-plastic lenses, however, is questionable when compared to acrylic. Readily available state of the art facet materials which are easily fabricated appear to be deficient in terms of long term durability (i.e., approaching a 20 year life or a life comparable to acrylic) in this application. Much more extensive testing than was conducted as a part of this project would be required in order to accurately characterize the life of the composite lenses.

Using the commercially available tempered soda lime glass, .125 inch thick and facet material about .040 inches thick on the average, material cost is:

	Material Cost/Ft^2		
	Type 1	Type 2	Type 3
o Soda lime glass, .125" tempered	$ .65	$ .65	$ .65
o Urethane facets, .04"	.35		
o Silicone facets, .04"		3.20	
o Low cost resin facets, .04" (set) mat.	$1.00	$3.85	.20 / $ .85

These costs are in truckload quantities. The Type 1 construction, using urethane facets, is thought to be representative of the medium cost plastic resin systems; Type 2, using silicone facets, is representative of expensive resin system in general; and Type 3 is estimated to be representative of general low cost resin systems. It appears that material costs of laminated vs monolythic acrylic lenses would be very comparable if a low cost resin system can be identified as a facet material. If this is the case, and if manufacturing costs remain comparable to that of acrylic casting then total lens cost of the composite lens would be expected to be comparable to that of cast acrylic at $2.50/ft^2.

The 10% drop in optical efficiency of the glass-plastic lens requires a 40% drop in lens price for system costs to remain equal to that of the cast acrylic Fresnel lens. It would seem that at the present time this would be difficult to achieve.

If the Jeannette low iron soda-lime glass were used to obtain the higher light transmission the glass price would rise to about $1.00 per square foot and in

combination with a low cost resin at $.20 per square foot a material cost of $1.20 per square foot would be achieved. This combination would be much more attractive and not be subject to the drop in optical efficiency penalty associated with normal soda-lime glass.

A considerable amount of aditional work must be performed to develop low cost glass-acrylic Fresnel lenses competative with cast acrylic lenses. The work required would focus primarily on both the development and testing of better facet material _and_ on practical large scale manufacturing processes to produce the laminated lenses.

RECOMMENDATIONS FOR FURTHER WORK

A number of areas which should be studied in order to further the development of laminated glass-plastic Fresnel lenses have been identified based on the work reported herein. These include:

Noncastable Materials

Materials which were not castable were excluded from this study. Materials which could be used in automated manufacturing processes such as injection, transfer or reaction injection molding should be explored. Exploration of such materials would lead to fabrication cost savings.

Weatherable Epoxies

Development work is being conducted by industry to improve the weatherability of flexible epoxies. These materials should be examined for application as a facet material as they become available.

Urethanes

Aliphatic polyester type urethanes with tailored UV and antioxidant stabilizers should be more environmentally stable than the urethanes studied in this project. The use of automatic military and mixing equipment would allow improved processing and could lead to acceptable facet manufacture processes.

Silicones

Silicone elastomers comprise a broad spectrum of compositions which could not be evaluated in this study. Silicones tailored for this application would be expected to both fabricate more readily and have better durability.

Acrylates

A variety of esters of acrylic acid lead to castable homo and copolymers of high flexibility and good weatherability. Development of such compositions were beyond the scope of this work but should be considered for future efforts.

Glass

Low iron soda lime glass manufactured by the float process has the potential of becoming a cost effective superstrate if market demand justifies production. Accumulation of applications which can generate this demand should be explored.

Tooling

The Fresnel lens mold design for generating plastic facets on glass can be greatly improved in terms of lens efficiency and automated lens ejection. Flexible type lens facet molds would appear to offer advantages in both cost and processing and should be explored.

Processing

A reasonable process for manufacturing the glass-plastic Fresnel lens has not been identified. Processes should be generally explored for cost efficiencies and product qualities in the process volumes anticipated for such lenses. Highly automated processes would be most desirable.

Optical Testing

The ability to obtain consistent measurements of optical efficiency is not available at Swedlow for Fresnel lenses intended for solar application. Methods need to be improved as such measurements are crucial to alternate lens type evaluation.

Optical Performance After Aging

More work needs to be done in the evaluation of lenses after long term outdoor exposure. The lenses should be placed in configurations which are representative of expected field applications in order to obtain realistic evaluations. Tests conducted to date have been comparative in nature and are not applicable to life prediction. A variety of exposure conditions including EMMAQUA and multiple geographic exposure should be conducted.

REFERENCES

1. Jebens, Robert W., _Laminated Fresnel Lenses_, Final Report on Sandia Laboratories Contract No. 07-7144, RCA Laboratories, August 1978.

2. Childers, Craig M., _Design and Development of Monolithic Acrylic Fresnel Lenses for Use in Point Focus PV Systems_, SAND 81-7040, December 1981.

3. Matalon, Lawrence A., _Test Report: Development of a Laminated Glass-Plastic Fresnel Lens_, July 21, 1980.

4. Hobbs, Robert B., Jr., _Design and Development of a Laminated Fresnel Lens for Point Focus PV Systems_, SAND 80-7137, January 1981.

5. Holdridge, D. W., _Development of a 10X Lens Concentrator_, Final Program Report to the U. S. Department of Energy, Albuquerque, N.M. for Contract No. EM-89-C-04-4197, March 1980.

6. Schuler, D. G., _Introduction to the Photovoltaic Concentrator Workshop_, Proceedings of the DOE Concentrator Systems Workshop.

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