Investigation of Reflective Materials for the Solar Cooker

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Introduction

A critical task in developing a solar cooker is to identify reflector materials that would be both suitable for this application as well as economical. FSEC has conducted an extensive search for available reflective materials. This has included contacting reflective materials manufacturers as well as national laboratories that are currently working with private industry in developing reflector that can be used primarily on large concentrating solar energy devices.

This investigation used a variety of resources. These included the FSEC solar library, web search engines, solar industry catalogs and directories, personal contacts, aluminum industry sources, solar cooker discussion groups, and a wealth of other investigative resources. A great deal of time has been spent on this search for the perfect material. The perfect material would of course be one that provides high optical reflectance, is ultra violet ray resistant, is durable in a variety of environmental and abusive conditions, is pliable, can be easily attached to a substrate, is available internationally, and last but not least, is economical.

Basically, FSEC could not find a product that would be considered a breakthrough in regards to those products currently being used on solar cookers. The materials currently being used range from common kitchen aluminum foil to complex films developed by major corporations.

The biggest disappointment was that 3M is no longer manufacturing the solar firms that were developed in the 1980s under the guidance of Mr. John Roche. The only valid 3M product (see VM2000 below) that could be used as a cooker reflector is currently manufactured for other applications and would have to be coated (for ultra violet ray protection) for use on solar cookers.

The other products described in this report that NREL has been investigating are cutting edge technology materials and still have a ways to go before they are ready for market. Actually, NREL is still working with the developers on both testing of the material as well as on production and manufacturing methods.

1. 3M VM2000 radiant mirror film

This material is a multi-layered polymeric film. The outside layer is polyethylene. It is metal free. Therefore non-corrosive and non-conducting. It is thermally stable to a temperature of 125 C. The manufacturer claims that the material has low-shrinkage. Unfortunately the material is not ultra-violet ray resistant. 3M can add an ultra-violet ray protectant at additional cost. (The special coating can only be applied at two facilities in Tennessee.) The material can also be coated with a 3M adhesive (#M 467MP) or can be

purchased without the adhesive. The reflective (optical luminosity is greater than 98. Reflects more than 98% of visible light. The drop off if reflectance at 700 nm is unfortunate, but is not detrimental for this application. It is a film like product that is flexible, lightweight and highly reflective. It is commonly used as an indoor reflective material for sun tubes and the like.

3M has verbally quoted a price of $1.25 per square foot (1,000 square foot minimum purchase). To that would be added $.30 per square foot for the ultra violet ray inhibiting coating. FSEC has repeatedly asked for a written quote and has not obtained such. In any event, the product is still in the development and testing stage as evidenced by NREL's Cheryl Kennedy report below.

3M does not seem to be interested in solar products. The manager of the section that developed solar films in the past have retired and 3M seems to have retired their interests in such products along with him. Nevertheless, 3M has stated (to NREL-C. Kennedy report below) that they would provide samples with improved screening layers for future testing.

FSEC Comments: The VM2000 material is only manufactured in the United States, as is the protective coating. In order to obtain this material, with the customized ultra violet ray protective coating, one would have to order a minimum of 1,000 square feet.

2. 3M SA-85 solar film

SA-85 is aluminum vapor coated on 2-mil polyester film with an outdoor weathering acrylic coating over the aluminum. (Per John Roche, the developer of the film.)

The former manager of the 3M section that manufactured solar films developed this film in the 1980s. There are several companies and individuals that use this material on their current solar cookers. Contact with 3M revealed that 3M would no longer be manufacturing this material and once the current supply in the field runs out, none would be available in the future.

FSEC comments: The 3M SA-85 film appears to be an ideal reflective material for use with solar cookers. Numerous solar cookers have used it successfully in the past. Unfortunately, the material is no longer being manufactured by 3M. 3M SA-85 is aluminized acrylic.

3. 3M Silver Flux material

This material is marketed by 3Mfor existing luminaires or as interior surfaces for luminaires. It maintains a specular reflectance of 85% and an overall reflectance of 90%. It is bonded to 0.7 mm treated aluminum and is ideal for producing rigid precision quality specular reflectors. It does not contain ultra violet ray protection and is unsuitable for outdoor use.

Following is the product specification:

3M Silverlux reflectors for fluorescent light fixtures, 2.5 mil polyester film with a specular metallized layer on front surface treated with an acrylic coating to suitable for protecting metallized layer from oxidation/corrosion and polyester film from ultra violet. degradation, covered with a removable premask and a pressure sensitive adhesive backing and low release liner and meeting or exceeding the requirements of EPA Green Lights Program and following requirements:

1. Tensile Strength: 45 lbs. per inch of width
2. Elongation at Break: 100%
3. Specular Silver Reflectors
   a. Specular Reflectivity: 95% at 1.5 degrees field angle using Devices and Services Specular Reflectometer; 92% at 0.5 degrees field angle (ASTM E 430)
   b. Diffuse Reflectivity: 2%
   c. Total Reflectivity: 97%
   d. Total Solar Reflectivity 95% integrated over air mass 2 solar spectrum.
   e. Reflective Life (ASTM G 53): 3% maximum loss of original Reflectivity after 1000 hours accelerator aging
4. Specular Aluminum Reflectors
   a. Specular Reflectivity: 85%
   b. Diffuse Reflectivity: 2%
   c. Total Reflectivity: 87%

FSEC comments: This product appears to be similar to the VM2000 film. (See VM2000 above.) An inquiry has been placed with 3M regarding the identification of this material – whether it is indeed similar to the VM 2000.

4. Acrosolar

This company uses and has a large supply of the 3M SA-85 reflective material that the company uses on solar concentrators. (Solar Laser Mirror) They have the material in 48-inch wide rolls. The material has an adhesive backing. Cost of the material from Acrosolar is $2 per square foot. Since the material is 3M SA-85 and 3M has informed FSEC that they are no longer be producing the material, there is no use considering it.

FSEC comments: See 3M SA-85 solar film above.

5. Acrylic Mirror

This material is half the weight of glass. It is shatter resistant and highly reflective. It is an optically perfect acrylic sheet that is vacuum metalized in a vacuum chamber. The sheets themselves are protected on the back by a durable scratch resistant coating and on the front surface be either a clear polyethylene film or a paper masking. The material can also be made with pressure sensitive backing. The manufacturing of this product is very complex. The cost of this material is also very high, which makes it unfeasible for this project. Close to $5 per square foot.

FSEC comments: The cost of this material makes it prohibitive for use in this project.

6. Alanod Aluminum

This is a German company that manufactures a variety of aluminum grades. It does market one product specifically for solar applications. That is Miro Extra bright. This material reflects super intensive spectral areas. The materials curve of the spectral reflectance follows the spectrum of the sun and it guarantees reduced diffusion together with high reflection values. Alanod states that their tests have proved the weather-durability of the additional lacquer used to provide external protection in demanding conditions. They also state that the lacquer does not reduce the optical properties of the material.

FSEC obtained samples and specification sheets of the material from the US distributor, Bloch Aluminum in Flushing, New York. Unfortunately the specification sheet states that the coating material is not ultra violet ray resistant. The United States distributor contacted the German manufacturer and was informed that the 4270 KK (being Miro 27 with clear varnish on the front and reverse side) is ultra violet ray resistant, but the protective film is not ultra violet ray resistant. FSEC is still investigating this issue. It may be that the "protective coating" referred to is actually a thin yellow film applied to protect the mirror surface during shipping. If that is the case then this material may be quite suitable for this project. The cost is somewhat higher than others, but the material would be indestructible.

In any event, FSEC obtained the cost of the material for information's sake.

MIROSUN - 4270 KK (MIRO 27 with clear varnish on the front and reverse side), C 1 natural tone with protective film on the front side
.020" x 49.212" coils
2000 lbs at US$ 7,71/lb
10000 lbs at US$ 7,62/lb
40000 lbs at US$ 7,37/lb
Delivery to be agreed upon

The above cost comes out to $2.15 per square foot.

7. Alcan Aluminum

Alcan is a major aluminum manufacturer. Contacts with this company have proved fruitless in finding a product that could be used in the solar cooker.

FSEC comments: This company produces aluminum products for industrial and commercial use. Competes with Reynolds aluminum in the household aluminum foil market. Other than standard aluminum foil, they do not have any special materials suitable for this project.

8. All Foils

This is a distributor and service center for thin-gauge metal foils, strips, or sheets. Their inventory includes aluminum in gauges of .00025 to .125 inches. The material they have available unfortunately is not designed for outdoor use.

FSEC comments: FSEC was advised that a protective coating of some type would have to be applied over the material for outdoor use. This manufacturer did not have any suggestions regarding this coating.

In discussing alternatives, the manufacturer also stated that the use of Mylar for this project would be unfeasible since Mylar would not hold up in outdoor use.

9. Aluminum, polished (General information on aluminum provided by FSEC staff)

FSEC Comments: Pure (99%+) aluminum develops a protective coating of aluminum oxide immediately on exposure to air (oxygen). This actually protects the aluminum from further oxidation by oxygen in the air (unlike iron which will continue to oxidize until there is nothing left but iron oxide – rust.) However, pure aluminum has poor structural properties. Therefore, aluminum that is used for anything structural is actually an alloy of aluminum. These alloys can be "polished" however, without some kind of protection (anodized or coated), they are subject to fairly rapid atmospheric corrosion.

One will often see white chalky pitting on unprotected structural aluminum products. Pure aluminum is also subject to severe corrosion from strong acids and bases like cement "lime" products will destroy it in very short order.

Thus aluminum products that are expected to last for extended periods of time must be coated with a protective coating.

10. Aluminum foil emergency blankets

FSEC comments: There are numerous products of this nature in the marketplace. Basically they are all offshoots of NASA research that initially developed this "blanket" technology for space application.

A search of various web sites and solar cooking discussion groups (Solar Cooker International archives) revealed that this product had been used in solar cooker application in the past. Several individuals had tried the product as a cooker reflector and were unsuccessful in long term application since, as they stated, "the material eventually falls apart."

11. Aluminum foil, heavy duty

FSEC comments: Common everyday kitchen application aluminum foil.

Here are some facts about standard kitchen aluminum foil provided by Reynolds Aluminum.

Reynolds Wrap® Aluminum Foil is the most versatile of all food wrapping materials. It can withstand both heat and cold. Reynolds Wrap® Aluminum Foil was first introduced in 1947. Since that time it has become one of the most immediately identifiable brands on the market. Reynolds Wrap® Aluminum Foil is 98.5% aluminum. The balance is primarily iron and silicon. These are added to give the strength and puncture resistance obtained only in the alloy used in Reynolds household foil. Reynolds Wrap® Aluminum Foil contains no recycled material and complies with U.S. Food and Drug Administration requirements for direct contact with food.

The brand that is known and sold all over the world is manufactured in two locations -- Louisville, Kentucky and Richmond, Virginia. Aluminum for Reynolds Wrap® Aluminum Foil is placed into alloying furnaces at the continuous cast plant in Hot Springs, Arkansas and heated until molten. It is then modified to the correct alloy chemistry and fed into a machine known as a "continuous caster." The continuous caster converts molten aluminum to a coil of metal by forcing it between large, water cooled chill rollers at several feet per minute. The aluminum is formed as a long sheet with a thickness of .045". It's rolled into large coils that measure 74 inches in diameter and weigh over 30,000 pounds! These coils are shipped in Reynolds' specially designed rail cars to Richmond and Louisville, where they are converted into the Reynolds Wrap® Aluminum Foil we all know – and love.

In addition, here are some little known application facts about aluminum foil that could have an impact on its use in solar cookers.

The difference in appearance between dull and shiny is due to the foil manufacturing process. In the final rolling step, two layers of aluminum foil are passed through the rolling mill at the same time. The side coming in contact with the mill's highly polished steel rollers becomes shiny. The other side, not coming in contact with the heavy rollers, comes out with a dull or matte finish.

The darkening of foil may be caused by moisture. This results in a buildup of aluminum oxide. This is a totally harmless substance that is naturally present on the surface of foil. Moisture tends to accelerate this buildup. (FSEC comment: This is acceptable for standard use of aluminum foil in standard ovens and kitchens, bit will have, in the long term, a negative impact when used as a reflector in solar cookers.)

Occasionally when aluminum foil comes in contact with a different metal or a food that is highly salted or acidic, small pinholes are formed in the foil. This is a harmless reaction that does not affect the safety of the food. It is difficult to predict, but may occur under the following conditions:

a. When aluminum and a dissimilar metal are in contact in the presence of moisture, an electrolytic reaction may occur causing a breakdown of the aluminum. To avoid this use aluminum, glass, ceramic, plastic or paper containers. Do not cover sterling silver, silverplate, stainless steel or iron utensils with aluminum foil.

b. A similar reaction may occur when salt, vinegar, highly acidic foods or highly

spiced foods come in contact with aluminum foil. The result of these reactions is a harmless aluminum salt. Some aluminum salts are used in medicines to treat stomach disorders. The food can be safely eaten; however, the aluminum salt particles can be removed from the food to improve the appearance of the food.

FSEC comment: Although these situations are questionably applicable to solar cookers the above facts indicate that standard aluminum foil is not as resistant and all purpose as many assume.

A little background on the most commonly used material in solar cookers. In 1919, the U.S. Foil Company, parent of Reynolds Metals Company was founded in Louisville, Kentucky to produce lead and tin foil. Then in 1926, the company entered the aluminum business, rolling aluminum foil for packaging. Today, Reynolds Wrap is made from 8111 alloy aluminum, at the thickest gauge specifications available in the marketplace. Reynolds Wrap® Aluminum Foil is 98.5% aluminum. The balance is primarily iron and silicon. These are added to give the strength and puncture resistance obtained only in the alloy used in Reynolds Wrap® Aluminum Foil.

The vast majority of built it yourself cooker plans include the use of this material as the reflector. This includes box, panel, as well as concentrating reflector type solar cookers. It is recommended primarily because of its worldwide accessibility and cost.

FSEC used heavy duty aluminum on a prototype cooker and discovered that the material was somewhat too fragile for long term usage. In addition, the material, although pliable, was not easy to handle and apply without creating wrinkles. Special 3M adhesive had to be procured to affix the material to insulation board. Standard white glue did not adhere very well. The material is so thin that it quite easy to damage.

12. Aluminized polyester

FSEC comments: This material discolored and faded after a year or two. (Per comments found in the Solar Cooker International archives.) Therefore, it appears that the material does not contain ultra violet ray inhibiting coatings or properties.

13. Anocoil aluminum sheet, 0.3mm thick

FSEC comments: This material is used in the Peru Children's Trust solar stove. Used 0.3 mm Anocoil grade 710.33 which was 86% reflective and exhibited a mirror quality.Anacoil is the largest independent manufacturer of lithographic plates in North America and supplies high quality plates to many leading publishers in North and Central America, Europe, and Asia. FSEC research indicates that the material used in solar cookers in the above Trust is not protected from oxidation.

14. Astro-Foil

Foil based reflective insulation material that is sold as an insulator. Bubble wrap type material is incorporated in the product and therefore would not be suitable for this application. Also, the manufacturer cannot provide optical property specifications. The

specification that they did provide, indicate that Astro-Foil is 5/16" thick, has a temperature range of –60 to 180 F, and has a reflectivity of 95-97%. The manufacturer states that the material can withstand solar radiation and environmental conditions and that it is available throughout the United States as well as in the Middle East and Singapore.

FSEC comments: This material is easily available but doe to the bubble wrap appearance and the manufacturer's inability to provide specification, it does not appear as a suitable reflective material for this application.

15. Clear Dome Solar – Solar Flex material

Triple-laminated, tear-resistant metallic fabric. Clear Dome states that this product is an offshoot of NASA research.

Manufacturer states that in comparison heat tests, their reflective material continuously beat any other material such as aluminum foil, glass mirrors, Mylar, etc. by 18-20% in heat generation. This is stated as being due to the excellent IR reflection properties that the other surfaces do not seem to reflect as well. The manufacturer also states that since their material reflects most of the IR, and because it has a metallic surface and not a plastic surface, there is little or no effect from IR exposure. In regards to degradation, the manufacturer has had samples outdoors for the past year in all types of weather, and except for a very slight loss in visible reflection, there have been no changes in the products heating capabilities. The manufacturer states that water has no effect on it. Food can be easily wiped off. Normal soap and water are recommended for cleaning. The product is also very scratch resistant and almost impossible to tear by hand. (FSEC can attest to this.) Yet knives and scissors easily cut the material. FSEC has also noted that the material can be scrunched into a ball and easily reconfigured into a flat position without creases, etc. remaining.

It is rated by the manufacturer to over 400 F and to –60 F. Clear Dome outdoor tests indicated no change in shape until the material reaches approximately 200 F. Above that temperature, the center plastic thermal barrier starts to shrink, causing a small ripple effect to the exterior metal surface. The shape changes slightly, but the material stays together.

The manufacture states that the material will take many bends before showing any wear. The material is thick, and feels like 8-10 layers of aluminum foil laminated together. The center is flexible and reinforced plastic provides excellent strength.

Clear Dome has found the best adhesive to be 3M contact cement. As long as the two surfaces are clean when the glue is applied, the two surfaces will remain bonded.

Unfortunately, Clear Dome could not provide any specification sheets on the product. Undoubtedly, Clear Dome is purchasing this material from a manufacturer, but FSEC has been unable to discover the manufacturer.

FSEC comments: FSEC purchased some of the material for testing with the Bernard prototype cooker. For 51-125 feet, the cost is $4 per square foot, which equals to $204 for 51 feet by 4 feet wide. The standard size is 2 feet by 4 feet. A 51-foot roll cost comes to $1 per square foot.

FSEC staff affixed the material to the prototype body (insulation board). 3M spray adhesive was used. The material is very pliable and quite easy to handle. Once affixed, it is very easy to remove wrinkles. Unlike standard heavy duty aluminum foil, the material is very sturdy. It cannot be ripped by hand; instead, it requires a knife or scissors to cut the material. This makes it ideal for rough handling and long term use. The material is so strong and yet pliable that one can form a large flat section into a ball and in turn smooth it out completely.

The material will be undergoing test with the Bernard prototype.

16. Heatshield (R+Heatshield)

This material is manufactured for use as radiant barrier. It contains 99% pure aluminum on both sides. Also contains a layer of polyethylene film for puncture resistance as well as polyolefin scrim for tear resistance. The material is available in solid or perforated structure. The material has the following specifications: 97% reflectivity, 3% emissivity, Class A flame and smoke rating, 12 lb/square inch tensile strength, and is 1.4 mil thick. The manufacturer claims that ultra violet rays will not affect the material. Costs have been requested from the manufacturer and should be received the first of the year.

Note that this material looks very much like the previously mentioned Clear Dome solar material.

17. Heatshield (R+Heatshield II)

This material is also manufactured for use a radiant barrier. It contains 99% pure aluminum on one side. Incorporates aluminized polyethylene (MPET) on the reverse side. It exhibits superior tear and puncture resistance. The manufacturer also states that it can withstand repeated pressure washing and is also available in a solid or perforated configuration. The material has the following specifications: 97% reflectivity on the foil side, 76% on the MPERT side, 3% emissivity on the foil side, 24% on the MPET side, Class A flame and smoke rating, 78 lb/square inch tensile strength, and is 1.4 mil thick. The manufacturer claims that ultra violet rays will not affect the material. Costs have been requested from the manufacturer and should be received the first of the year.

Note that this material looks very much like the previously mentioned Clear Dome solar material.

18. Low Met

This is a silicon based spray on material that is used (and marketed) primarily as a radiant barrier material

FSEC comments: This material would not be suitable to this project due to its “diffuse reflectance” properties.

19. Metalized Products, Inc.

Metalized Products, Inc. is a leader in developing and manufacturing protective, reflective, decorative, functional and performance coated products using plastic films, paper, and textiles as well as producing laminates for these products.

The following materials are sold:

Astrolon – A family of super-light radiant barrier materials perfectly suited to application ranging from emergency medical care to outdoor recreation.

NRC-2 – A family of high-performance thermal insulating materials

Heat Shield - Vacuum aluminized film used as a thermal/vapor barrier similar to that employed as radiation barrier on the Apollo Command and Lunar Modules.

Decorative Papers - MPI's line of non-laminated holographic papers, boards and films provide excitement to gift wrap, cosmetic and security markets.

Mirrorbrite - Mirrorbrite is a high gloss, metallic paper or board with a mirror-like surface. Mirrorbrite is used in both packaging and printing applications.

Prismabrite: A holographic paper available in standard or customized patterns used in both packaging and printing applications.

FSEC comments: Mirrorbrite was investigate. It appeared to be the only possible product from this manufacturer that would be applicable to this project, but it does not have UV inhibiting characteristics and is therefore unsuitable.

20. Mirrored Plexiglas

FSEC comments: Standard Plexiglas with mirror coating. Can be used for ray testing only. Not outdoors durable and very expensive. Can order from Brevard Plate Glass - Susan. Comes in 4 foot by 8 foot sheets - $136 (Includes 15% discount for not cutting) 1/8" thick. Can cut for us. Then it's $5 per square foot.

21. Mirroflex

Mirroflex is a composition of rigid high impact plastics, vacuum metalized and bonded together to create highly reflective, unbreakable mirror-like sheets. Mirroflex is a reflective, impact resistant plastic with unusual surface treatments including silver, gold, brass, brushed metallics, wood grains and granites. This material is very easy to fabricate. Mirroflex is available in sheets or rolls (depending on the thickness).

Mirroflex thermo plastic sheet and roll programs are also available as metallic trim. In roll form, it has a pressure sensitive adhesive backing for use in decorative metallic trim applications from 1/4" and up in 1/8" increments. Available in polished aluminum, brass & gold, brushed aluminum & brass, black and more.

Mirroflex sheets are available in all metallic colors listed above in 2' x 8' and 4' x 8' sheets, varying in thickness from .020" to .025". Also available in a large selection of wood grains, granites, solid colors and specialty finishes suitable for interior and exterior application.

Mirrotiles are fabricated in Mirroflex to fit standard suspension ceilings where an easy to use, easy to fabricate very low-cost mirrored ceiling tile (chrome or gold) is desired.

FSEC comments: Mirroflex materials are primarily manufactured and marketed for interior decorative purposes. Without investigating the optical, solar, and durability properties of this manufacturer's products, it was determined that the cost is too prohibitive for this solar cooker project.

22. Mylar

FSEC comments: Dr. Steven F. Jones, Professor of Physics at Brigham Young University, reports in his paper "The Solar Funnel Cooker," Solar Cooker International archives, that aluminized Mylar was used in the development of the funnel solar cooker. Dr. Jones reported that aluminized Mylar was a good reflective material but was "relatively expensive and rather hard to come by in large sheets." (Therefore, the funnel cooker used standard aluminum foil instead.)

It has been noted previously that Mylar does not have long term weathering characteristics required for this solar cooker product and will not hold up to outdoor use.

FSEC comments: Metalized Mylar was used at the University of Texas, Pan American, Edinburg, Texas on a parabolic solar concentrator. The material was inadequate as "it yellowed along the edges and peeled after only two months. The film used was metalized Mylar and it was bonded to several layers of soft woven and heavy woven fiberglass using amine epoxy."

23. NASA product spin offs

Through space use, a once commercially obscure product has become a booming commodity

Metallization is the coating of a material with a fine mist of vaporized metal to create a foil-like effect. It's not a space-age invention; in fact, the concept dates back to the 19th century. Metallization is, however, a prime example of how space use of an existing product or process sometimes triggers a chain reaction: the space need creates a market, the new market inspires further development, which expands the range of applications. Eventually, the once commercially obscure product becomes a booming commodity. In the case of metallization, space use helped transform a small-scale manufacturing

operation producing decorative metallized plastics into a flourishing industry marketing materials for scores of applications.

It started in the early days of the space program when NASA was experimenting with large balloon- satellites as orbital relay stations to reflect communications signals from one Earth location to another. The material for the balloon skin had to be highly reflective to ³bounce" the radio signals. It also had to inflate in orbit to a diameter roughly equivalent to the height of a ten-story building, but be exceptionally thin and lightweight to fold into a beachball-size canister for launch from Earth. The solution was a new type of plastic film coated with a superfine mist of vacuum- vaporized aluminum.

NASA subsequently used the material as a reflective insulator to protect astronauts from solar radiation and sensitive spacecraft instruments from extreme temperatures. The widening field of applications spurred R&D by manufacturers to improve vacuum metallizing techniques. This, in turn, led to development of diverse commercial products, including insulated outdoor garments, life rafts, reflective blankets, wall coverings, window shades, food packaging, candy wrappings, and photographic reflectors.

Metallized Products, Inc. (MPI), Winchester, Massachusetts, was one of the companies that worked with NASA on the original space materials. MPI continues to supply metallized materials for space use and has developed lines of industrial and consumer-oriented metallized film, fabric, paper, and foam. One of the most successful MPI products is TXG laminate, once employed by NASA as a reflective canopy for visual and radar detection of the rafts in which returning Apollo astronauts awaited pickup by ships or helicopters. TXG not only is super reflective, but nonporous, waterproof, and rot-proof. Subsequently, Winslow Company Marine Products, osprey, Florida, obtained a license for commercial production of the survival raft. In cooperation with MPI, Winslow improved the strength and thermal characteristics of TXG so that its survival rafts would provide maximum protection from heat, cold, wind, and rain.

A reflective kite of gold TXG produced by Solar Reflections, Inc., Fort Lauderdale, Florida, serves as a highly conspicuous distress indicator in an emergency. The SOS Signal Kite can be flown as high as 2OO feet to enhance radar and visual detectability. It provides campers, hikers, and mountain climbers with a lightweight, easily portable emergency signaling device, and boaters with a convenient substitute for bulky dish devices. Made of metallized nylon, the kite spans six feet but weight only six ounces.

Connecticut Advanced Products, Glastonbury, Connecticut, has adopted lXG for its Thermoguard heat shields, custom-tailored reflective curtains that cover the windshield and windows of parked aircraft to protect avionics equipment from heat buildup and ultraviolet radiation. In a similar application, the Starshade~ from Star Technology Corporation, Carbondale, Colorado, is a multilayered automatic shade system for large windows in commercial or residential buildings.

Among MPI's own products are various protective fabrics that retain up to 8O percent of the user's body heat, helping to keep a person warm for hours in cold weather crises or to prevent post-accident shock. All are remarkably compact. The Space* Emergency Bag,

for instance, opens into a three-by-seven-foot personal tent/blanket and then folds into a three-ounce package the side of a deck of playing cards.

(Photo Caption) Thermoguard heat shields, windshields, and window curtains custom-tailored by Connecticut Advanced Products from TXG metallized fabric reflect the sun¹s rays and protect long-parked aircraft from heat buildup and ultraviolet radiation that could damage its sensitive and expensive avionics equipment.

(Photo Caption) Fishing boat captain Kurt Barlow deploys an SOS Signal Kite, a highly reflective distress signal made of metallized nylon that can be elevated to 200 feet for best visibility. Barlow also is wearing a reflective cap for protection from the sun.

(Photo Caption) Among the Applications of reflective TXG is the Emergency Blanket manufactured by Metallized Products, here used by a ski patrol to protect a skier shaken by a fall. The blanket, which folds into a package no bigger than a deck of cards (bottom left), retains up to 80 percent of the user¹s body heat.

(Photo Caption) The Winslow Radar Reflector Life Raft features a canopy made of TXG that reflects the sun¹s ray¹s like a mirror, enabling radar or satellite sensors to spot it, and also provides thermal insulation to occupants.

(See: http://vesuvius.jsc.nasa.gov/er/she/spinoff.html)

Metallization is the coating of a material with a fine mist of vaporized metal to create a foil-like effect. NASA used material as a reflective insulator to protect astronauts from solar radiation. Later used as insulated outdoor garments, life rafts, reflective blankets, etc.

Metallized Products, Inc. (see above) worked with NASA on the original material design and continues to supply metalized materials for space use and has developed lines of industrial and consumer oriented metalized film, fabric, paper, and foam.

One of the most successful materials developed. Reflective canopy for visual and radar detection. Material is super reflective, nonporous, waterproof, and rot proof. Used in boating life rafts. Similar to the Cleardome product listed above.

24. National Renewable Energy Laboratory (NREL) publication

FSEC staff came upon an National Renewable Energy Laboratory (NREL) FACT Sheet titled "Concentrating Solar Power Research" by Gary Jorgensen (12/98, FS24863) that mentioned that the Sun Lab researchers are " developing new reflective materials, such as advanced polymer films that can be produced at a fraction of the cost of glass mirrors and have excellent optical and wear-resistant properties." Contacted Gary Jorgensen at NREL via e-mail regarding this matter.

FSEC comments: Initially suspected that the material might be the 3M VM2000 film - or something similar. Never received a reply from Jorgensen. See NREL's Cheryl Kennedy comments below.

25. NREL Publication

This publication provides good insight into the near current status of solar reflective material research.

"Progress Toward Achieving a Commercially Viable Solar Reflective Material" by C. (Cheryl) E. Kennedy and R.V. Smilgys, NREL/CP510-24058. The description below is from this report.

Solar thermal technologies use large mirrors to concentrate sunlight for renewable power generation. The development of advanced reflector materials is important to the viability of electric production by solar thermal energy systems. The reflector materials must be low in cost and maintain high specular reflectance for extended lifetimes under severe outdoor environments.

Production processes associated with candidate materials must be scalable to mass production techniques. A promising low-cost construction uses a stainless steel foil substrate with a silver reflective layer protected by an optically transparent oxide topcoat. Thick (2 to 4 micron), dense alumina coatings provide durable protective layers. The excellent performance of alumina-mated reflector materials in outdoor and accelerated testing suggests that a larger field trial of the material is warranted. The key to producing a greater quantity of material for field deployment and testing without incurring substantial capital is the use of a chilled drum coater. An existing chamber is being modified, and the deposition rate will be increased prior to the installation of a drum coater to produce-1 ft wide by 10-ft long strips of solar reflector material. The production and performance of these materials are discussed.

Silvered PET protected by 1BAD deposited alumina represents an advancement in solar reflector durability. Preliminary results have shown an initial solar-weighted hemispherical reflectance of 95% and excellent optical durability in both accelerated and outdoor (Colorado) exposure testing.

Additional issues to address include determining the minimum coating thickness needed to ensure optical durability, increasing the deposition rate, testing the long-term mechanical stability of the material under biaxial stress, and field testing the material. Research into a better stainless steel leveling layer is being pursued. The alumina-coated reflector material under development offers promise as a commercially viable solar reflector material. The deposition system at SAIC is large enough and has sufficient capability to support a range of reproduction scale coatings work and the new state-of-the-art deposition system at NREL will allow the development of additional innovative coatings to be prototyped.

FSEC note: This is in the realm of national laboratory research and development into products that can be used on large parabolic and dish type concentrating solar collectors. Mass production is not available. See further information obtained from Cheryl Kennedy, below.

26. NREL, Cheryl Kennedy

Cheryl Kennedy provided information on the latest NREL tested reflectors. This information is based on Cheryl's report, "Summary of Status of Most Promising Candidate Advanced Solar Mirrors (Testing and Development Activities), 30 Sep 2001" (Have Power Point presentation.)

Alanod Front Surface Alumized Reflector product
(Note: This is the Alanod product reviewed in this report)
-Front surface aluminized reflectors using a polished aluminum substrate, an enhanced aluminum reflective layer, and the formation of a protective oxidized topcoat (alumina) were shown to have inadequate durability in industrial environments. Samples with a polymeric overcoat to protect the alumina layer have improved durability. Samples have survived >3 years outdoor exposure in Koln, Germany under the SolarPACES project.
Has a polymeric overcoat to protect the aluminum. The acrylic overcoated material failed in accelerated testing and was replaced by fluoropolymer overcoat. The new formulation is still being evaluated.
Consists of:
-Protective Polymeric Overcoat
-Alumina
-Aluminum reflective layer
-Polished aluminum substrate
_Around $2/ft 2.

This is a commercial product that has been untested for solar applications and is still being evaluated by NREL!

Reflec Tech
_Base commercial silvered polymer
_92% hemispherical reflectance
_Cost about $1.50/ft2
_Contacted Reflec Tech: product not commercially available yet but developer will contact FSEC when the product is commercially available.

Other materials tested were unsuitable; mirrors, failures, etc.

27. NREL, Cheryl Kennedy

NREL-Cheryl Kennedy Cheryl sent me another materials testing report. "Optical Durability Testing of Candidate Solar Mirrors, March 2000." Report states that the following were excellent tested materials (durability wise):

- Thin glass, thick glass, SA-85 and ECP-305+
  Glass is of no use to the application for this solar cooker project.

FSEC comments: The SA-85 and ECP-305+ were made by 3M and will no longer be manufactured once current stock in the filed is consumed.

The report states that these materials can be characterized as intermediate and require further improvement

- All polymeric construction
- Alanod's aluminized reflector
- A metallized polymer (ECP-305)
-

FSEC comments: Once again, ECP-305 is a 3M product that will no longer be manufactured. Note that NREL continues it's evaluation of this material and is also evaluated in 2001 – See Item # 24 above.

The report also states that the following were characterized as poor and unsuitable for solar reflector applications:

- Metallized polymer (SS-95)
- Metallized fluoropolymers (until specularity can be sufficiently improved)
- Constructions in which adhesives are in direct contact with a silver reflective layer

28. NREL Technology Transfer Technologies Available for Licensing: "Durable Metallized Polymer Mirrors"

The following is from an information report developed by NREL.

NREL researchers have made several modifications in the construction of Silvered Polymer solar mirrors which improves their optical durability and resistance to delamination failure. One innovation is to interpose an oxide layer between the polymer film and the silver reflecting layer. The oxide layer impedes the initiation of delamination and also impedes the propagation of delamination if initiation occurs. The oxide layer also provides protection to the silver and slows corrosion. In a preferred construction, there is a copper layer between the silver and the adhesive, which significantly helps to slow corrosion of the use silver. Silvered polymer solar reflectors are finding increasing use in parabolic trough and dish concentrator applications. At present the 3MCompany of Minnesota is the major supplier of these polymer mirrors. Their commercial product, ECP-305+, developed in collaboration with NREL, incorporates the protective black layer of copper along with a delamination resisting alternative adhesive. A number of industrial partners, including Industrial Solar Technology and Cummins Power Generation, are field testing these mirrors at the present time.

FSEC comments: In a follow-up to this report, FSEC contacted Ken May at Solar Technology and was told that the 3M silver film (ECP-305) never made it and that they now use the 3M SA-85 aluminized acrylic film on their reflectors. Unfortunately, 3M has discontinued using this material and it will no longer be available once existing stock is used up.
FSEC comments: Barbara Kerr states in an e-mail posted on the Solar Cookers International web site archives that she also uses the SA85 since it is very durable and UV resistant. It is also scratch resistant. Barbara is associated with Solar Cookers International and is the author of "Spreading Solar Cooking, A Field Guide. Second

Expanded Edition, 1997," and is a well known authority in the use of solar cookers internationally.

29. Polyester based reflective materials

FSEC comments: Comments discovered in the Solar Cookers International archives attest to the fact that "this material does not stand sun-radiation for very long."

30. "Optical Properties and Exposure Tests of Solar Reflective Materials", Th. Fend, M. Sanchez, A. Morales, P. Rietbrock, M. Boehmer. (Note: Test of Various Solar Reflective Materials. SiO2 is quartz, a form of silica, or silicon dioxide.) Presented at the International Solar Energy Society Eurosun 1996 Conference, http://wire0.ises.org/wire/doclibs/EuroSun96.nsf/H/O?Open&697090DABF8B8F04C12565E60037325C

31. Ra Bar Products Inc

Aluminized foil material that incorporates kraft paper backing. Marketed as a radiant barrier material. Reflectance characteristics have not been obtained from the manufacturer.

FSEC comments: This is a local company that provides radiant barrier material. FSEC obtained aluminized foil material with kraft paper backing for prototype testing. The material is .0003/30 lb aluminized foil and at $.04 per square foot is economically attractive. FSEC has affixed this material to one of the Roger 7.7 cookers that will be tested at FSEC.

It is easy to adhere to a backing when using 3M adhesive spray material. The material FSEC acquired came in a large roll. Creases were evident in the material which undoubtedly resulted from the rolling process. FSEC staff was not able to remove the creases during the application to the cooker backing. Interestingly, the kraft backing more than likely was a positive feature, as it tended to allow better adhesion to the backing material.

32. Roche, John

FSEC comments: Mr. Roche is the former 3M scientist that developed numerous 3M solar firms during the 1980s. He is currently retired and is associated with the Solar Oven Society. FSEC staff discussed the current project with Mr. Roche who provided innumerable insight into solar ovens and reflective materials. Currently he uses the 3M SA-85 solar reflective film on his cookers, but acknowledged that 3M is no longer manufacturing this product and once it is used up, it will no longer be available. John did send FSEC a sample of the SA-85 material.

It is this author's opinion that 3M, and the solar industry at large, have lost a great advocate (and developer) within 3M of solar films and related products with the retirement of John Roche from 3M. Actually the current 3M films division representative suggested to FSEC staff that we contact Mr. Roche to obtain information on solar films.

3M did not seem very enthusiastic about solar films. This is probably in large part due to the very small demand and use of this material.

FSEC comment: The following is taken from the above referenced paper.

In the present study a number of promising new reflective materials for solar thermal energy conversion have been exposed to real outdoor conditions at 8 test sites in the U.S. as well as in Spain and in Germany under various climatic conditions. Further tests have been performed in a simulating weather chamber. Weather and air pollution data have been monitored to reveal possible lifetime limiting environmental factors. Materials investigated were anodized aluminum, SiO 2 -coated silver and SiO 2 -coated aluminum processed via the sol gel technique, silvered polymer and aluminized polymer mirrors and finally several kinds of silvered glass mirrors. Theoretical performance has been determined by measuring the hemispherical reflectance as a function of exposure time with a dual beam UV-VIS-IR spectrometer equipped with an integrating sphere. Microscopic investigations have been performed additionally to characterize material degradation.

Materials
In general the cooperation within the SolarPACES program foresees, that any participant may distribute reflector samples to test sites of the partners on a "request to be weathered" status. However, only those materials promising to meet the performance goals are distributed to all test sites. Besides these "close to the market" materials, those types being in developmental states are previously tested in a weather simulator or at one outdoor site. The reflective materials investigated in this study can be classified into the following groups:

Silvered glass
The 3 types of silvered glass materials used in this study consist of a glass substrate silvered from the backside and sealed with an oxidation protective layer. A low iron content float glass is used with optimized transmission properties in the UV VIS-IR range. The materials have been applied successfully in the LUZ-LS3 collectors (Flabeg 4 mm glass/silver) as well as in a stretched membrane heliostat project (Glaverbel/Hirtz 1 mm glass/silver) and in dish/stirling systems (Steinmuller 1 mm glass/silver) [7].

Coated Aluminum:
The 3 sheet aluminum materials employed in this study consist of an aluminum substrate (0.8 mm) carrying a reflective layer of pure aluminum and an oxidation protective thin ceramic coating. SOLARdirect provides an anodized and Alanod and Anofol/Metalloxid a PVD coated surface.

Metal/Polymer:
ECP305 Plus is a silvered weatherable acrylic film with an adhesive layer on the back side. Two kinds of substrate materials (aluminum, float glass) are tested. SA85 is an aluminized polymer material with an acrylic protective overcoat. Float glass and stainless

steel were tested as substrates. Sunflex consists of an aluminized Hostaflon film with a protective film on the back side. Samples have been exposed without any substrate.

Sol-Gel coated silver/aluminum:
These materials, fabricated in the CIEMAT labs in Madrid consist of different kinds of substrate materials (glass, aluminum), a reflective film (aluminum, silver) and an oxidation protective layer processed via the sol-gel route [8].

Results/Discussion
The solar weighted hemispherical reflectance values RS of selected weathered samples are resumed in Table 3, the reflectance values of the accelerated weathering tests are listed in Table 4. In general it can be stated that glass/silver materials exhibit good weatherability. They do not exhibit markedly losses in solar reflectance neither after outdoor exposure nor after accelerated weathering. Furthermore no visible damage ocurred due to corrosion from the edges or from the surface.

The polymer/silver materials exhibit good results in the outdoor test (which is of course too short to draw final conclusions), but a slight decrease of the solar reflectance after accelerated weathering. In Fig. 3, the hemispherical reflectance is plotted as a function of wavelength. It shows, that the loss in reflectance is restricted to the wavelength intervals 400 - 700 nm and 1850 - 1950 nm.

The results from the accelerated weathering tests in combination with the preliminary outdoor exposure tests provide information on possible lifetime limiting environmental factors. Oxidation attack of the reflective layer by means of surface flaws in the protective coating is a limiting factor for all materials except silver/glass. In contrast to polymer surfaces, which predominantly suffer from radiation in the UV-range, PVD-coated aluminum materials are attacked by corrosion, which is accelerated by means of moisture probably in combination with atmospheric and rain pollutants. The applicability of those materials is not yet proven and results from all test sites have to be compared to clarify the degradation process and to perform reliable lifetime predictions. The investigated glass/silver materials confirm their known good weatheribility and reflectance properties.

Material	Manufacturer/Supplier	R_s (t=0) (%)	R_s(t=0.5y) (%)
4mm glass/silver	Flabeg (D)	93,8	93,8
1mm glass/silver	Steinmüller (D)	94,0	93,5
1mm glass/silver	Glaverbel (B)/Hirtz (F)	94,6	94,6
Miro 2 - 95	Alanod (D)	88,6	85,4
Miro 2 - 96	Alanod (D)	91,1	
Anod. aluminum	SOLAR direct (D)	86,8	84,8
1000.90	Anofol (E)/Metalloxid (D)	89,8	83,0
ECP305+ /aluminum	3M (US)	95,6	95,7
ECP305+/glass	3M (US)	96,1	95,8
Sunflex (polymer/aluminum)	HTC Solar (D)	86,9	<80
SA 85/glass	3M (US)	88,1	88,1
SA 85/steel	3M (US)	88,2	88,1

Table 3: Solar weighted hemispherical reflectance values R_s of selected weathered samples (outdoor exposure Köln)

Material	R_s (t=0) (%)	R_s (t=2000h QUV) (%)	R_s (t=4000 h QUV) (%)
1mm glass/silver (Glav./Hirtz)	94,6	94,7	94,5
Miro 2 - 95 (coated aluminum)	88,6	88,1	88,2
ECP305+ /glass	96,1	95,4	94,8
Sunflex (polymer/aluminum)	86,9	<50[4]	-
Sol-Gel coated silver	95,5	94,0[5]	-
Sol-Gel coated aluminum	91,0	-	-

Table 4: Solar weighted hemispherical reflectance values Rs of selected samples after accelerated weathering in QUV weather simulator ([4] reflective aluminum film totaly removed)

FSEC Note: Other than the 3M material (which is no longer manufactured by 3M), the other materials are not suitable being glass, too expensive, developmental, etc.

33. United Aluminum

Manufactures custom rolled aluminum coils. Darwin Curtis' son, John, obtained aluminum from this company for a solar cooker that he designed.

Determination will have to be made whether this aluminum has a protective coating to prevent long term oxidation. Or, if that coating is ultra violet ray resistant.

34. FSEC general conclusions regarding the selection of a reflective material.

Basically, FSEC could not find a product that would be considered a breakthrough in regards to those products currently being used. The biggest disappointment was that 3M is no longer manufacturing the solar firms that were developed in the 1980s under the guidance of John Roche. The only valid 3M product is currently made for other applications and would have to be coated for use on solar cookers. 3M does not seem very interested in working with FSEC on this project. Numerous requests for formal price quotes and the realistic feasibility of providing the material with the protective coating have not produced any results. Therefore, this author suspects that 3M is not that

interested in marketing this product. Actually, I believe the problem is that they are \not interested in coating the existing product for ultra violet ray protection.

The other products described in this report that NREL has been investigating are cutting edge technology materials and still have a ways to go before they are ready for market. Actually, NREL is still working with the developers on both testing of the material as well as on manufacturing methods.

Currently FSEC will be testing the solar cooker prototype using the RaBar and Clear Dome metalic foil material.