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August 1979

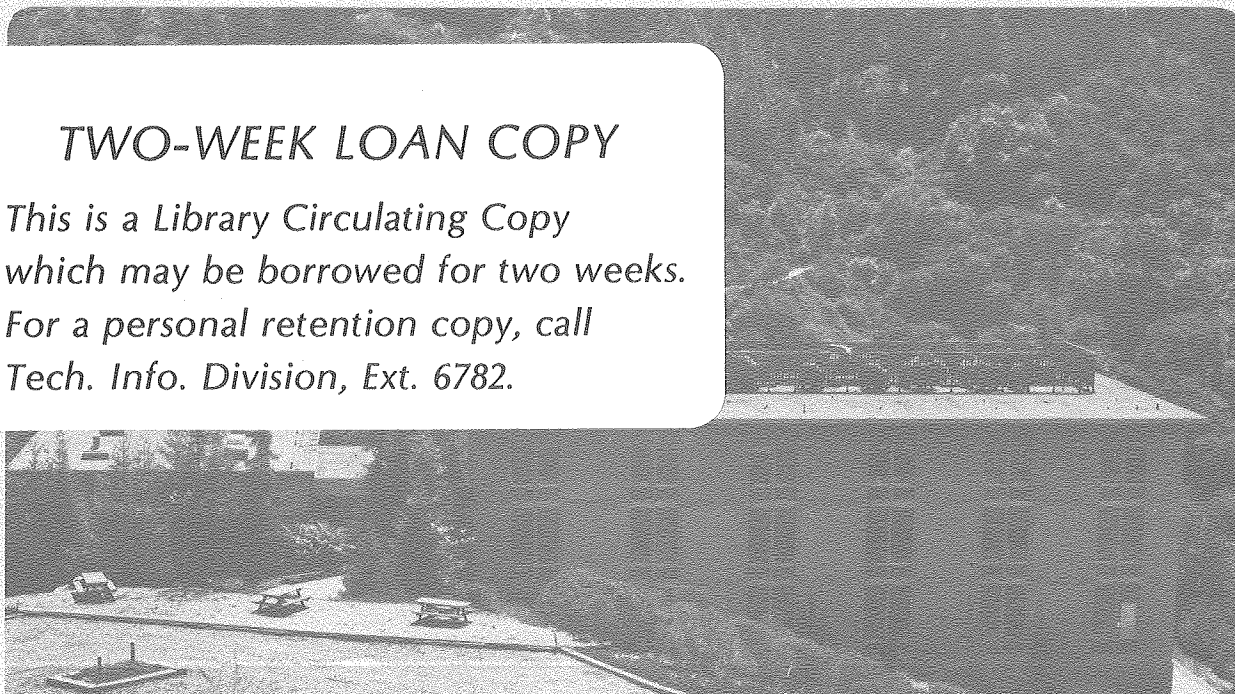
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METAL FOILS FOR DIRECT APPLICATION OF ABSORBER
COATINGS ON SOLAR COLLECTORS

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ABSTRACT

The basic materials and processing associated with the production of coated metal foils for solar collector absorber surfaces are discussed. Also covered are details of heavier metal strips for direct fabrication of solar collectors. Techniques including bonding methods and the use of adhesives are surveyed. Commercial solar foil manufacturers are covered, chiefly Berry Solar Products and Ergenics, along with the new research efforts in this area. In conclusion, advantages and disadvantages are outlined, with specific recommendations.

INTRODUCTION

The concept of bonding selectively absorbing foil to absorber plates for solar collectors is a unique one. The production of this foil absorber consists of first treating the foil with a selective finish in a continuous manner. The process is completed when adhesive is applied to the foil and the combination bonded to an absorber plate. An extension of this concept is the continuous coil finishing of thick strip suitable for direct fabrication of solar collectors.

With a continuous plating operation, the specific problems associated with absorber finishing and collector manufacture are separated into their proper areas. With this process the finisher is essentially freed from problems associated with specific collector sizes, designs and base metals. The requirements now become concentrated on quality and uniform finishing of continuous metal, although it is very important that optical parameters such as solar absorptance (α) and infrared or thermal emittance (ϵ) are monitored.

Foils are loosely defined in this study as thin metal less than 75 microns (0.003 in.) in thickness with about the consistency of household aluminum foil. The use of foil for solar collectors requires a high temperature bonding agent, which can either be applied by the finisher or the user. Adhesives and methods of foil application are of major considerations when a foil absorber is considered; details

pertaining to adhesives and foil bonding techniques will be discussed subsequently. Possibly the major drawback with foil absorbers is that foils do not easily cover complicated collector geometry, that is they are best suited for flat or semi-flat surfaces.

Another absorber concept is that of metal strip or thick foils greater than 75 microns (0.003 in.) with the upper thickness limit currently being about 305 microns (0.012 in.) for the Berry process. This selective absorber coated strip material can be used directly for fabrication of solar collectors, the major requirement being that the collector coating be durable enough to withstand various mechanical processing and bonding operations. The easiest method of making a flat plate collector is by directly attaching pipes on the back of this absorber strip. Techniques such as high frequency welding, soldering, adhesive and mechanical fitting are used for pipe bonding. The principal problems associated with strip is that of protection of the absorber surface from overheating and abrasion during forming and bonding operations.

The basic challenge for the metal finishes is being able to adopt conventional batch chemical conversion and electrodeposition processes to continuous finishing of foil and strip coils. Only two commercial companies have already done this. Berry Solar Products (Edison, N.J.) produces a product known as "SolarStrip", which is black chrome on nickel plated copper and Ergenics, a Division of MPD Technology Corp. (Waldwick, N.J.) fabricate a special nickel foil absorber marketed as "Maxorb". These processes, along with manufacturers' experience and research efforts, will be discussed in the following sections.

SOLAR FOIL ABSORBERS

Berry Solar Foil Process

Black chrome has become the most popular, but costly, selective surface for solar collectors (1). A commercial concern, Berry Solar Products, has developed a foil, continuously plated, with black chrome. This foil is sold without an adhesive backing; the choice of adhesive is left to the collector fabricator. Also, they market a heavy foil or strip for direct fabrication of collectors; this concept will be discussed in a later section. Both thin and thick foils are sold under the trade name "SolarStrip".

The basic foil consists of a conventional but proprietary black chrome on nickel plated copper strip. The nickel interfacial layer is necessary for corrosion resistance. In addition to the electroplating the finished absorber surface is covered with a polymer, quick release film, which protects the surface from abrasion during handling and subsequent fabrication. To finish a continuous foil the electroplating parameters have to be adjusted from those of the batch process. This

process utilizes a small bath volume of nickel and black chrome which results in less waste water management but in turn requires better control of chemistry.

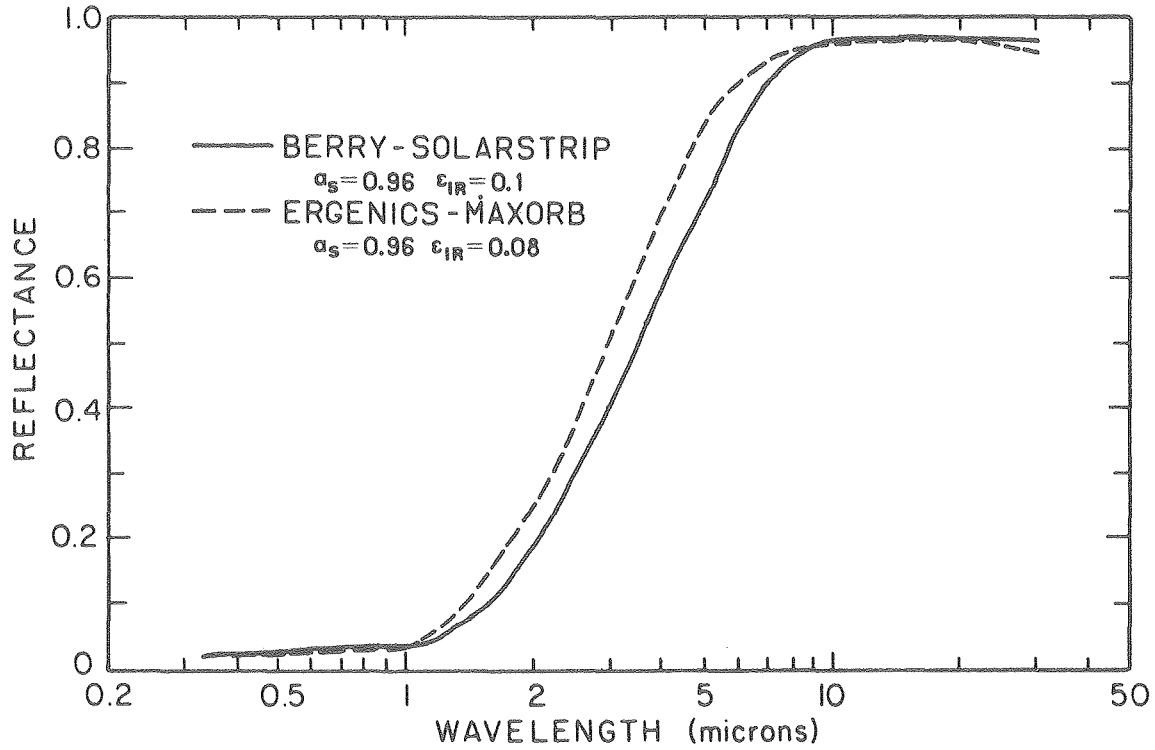
The solar selective properties for Berry black chrome are quite similar to those of conventional batch process black chrome. This manufacturer guarantees the coating to have an average solar absorptance, $a_s = 0.95 \pm 0.02$ and a thermal or infrared emittance, $e_{iR} = 0.10 \pm 0.02$. These values were obtained with a Willey Alphameter and (room temperature) emissometer (2). Spectral reflectance for Berry Solar foil is shown in Fig. 1. The typical surface microstructure, along with an elemental X-ray analysis (EDAX) is shown in Fig. 2. This microstructure is typical of batch plated black chrome except for the rolling lines and the effect of preferential plating, (3).

Maxorb Solar Foil Process

Another successful continuously coated foil is known as "Maxorb", developed by Ergenics, a division of MPD Technology Corporation. Maxorb consists of a mixed nickel-chromium oxide on a 12 micron (0.0005 in.) adhesive backed nickel foil (4). The oxide layer is created by a proprietary chemical conversion process consisting of an automated and electronically controlled acidic oxidizing bath. The surface structure of this interesting selective absorber foil is shown in figure 3; also, an elemental analysis is noted. This coating has some theoretical implications because it is one of the few chemical conversion coatings which exhibits excellent solar selectivity (see Fig. 1.). This foil possesses a solar absorptance of $a_s = 0.97 \pm 0.01$ and thermal emittance of $e_{iR} (100^\circ\text{C}) = 0.10 \pm 0.03$. These measurements were taken with a Willey Alphameter and a McDonald Emissometer (4).

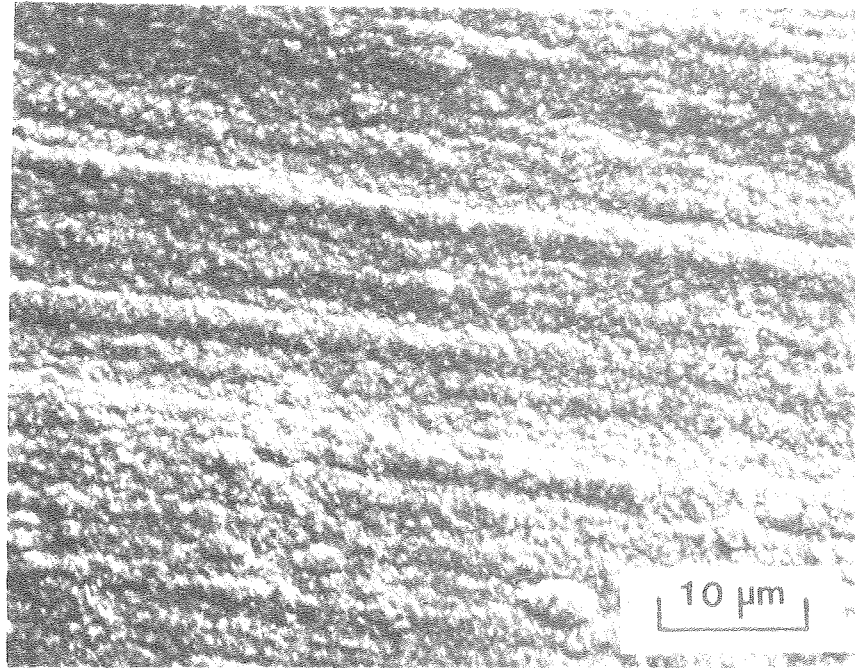
The mixed oxide absorber consists of a ~ 200 Å top layer which is a nickel-chromium oxide, NiCrO_x . This top coating chemically grades to a predominately nickel oxide layer with chromium as a minor constituent. The depth of this coating extends about 0.3 microns to the nickel interface. This data was determined by Auger depth profile analysis (5). It must be noted, too, that the exact compounds are unknown as well as their distribution in the oxide. It may be possible that nickel and chromium exist to some extent in metallic forms. Topological roughening is also seen, which would act to increase solar absorption. As a result of this analysis, it was concluded that this surface might exhibit solar selectivity by a combination of mechanisms including surface scattering, optical interference and semiconductor/metal tandem effects.

The manufacture of nickel foil is produced by continuous electroforming so that it complements the blackening treatment.

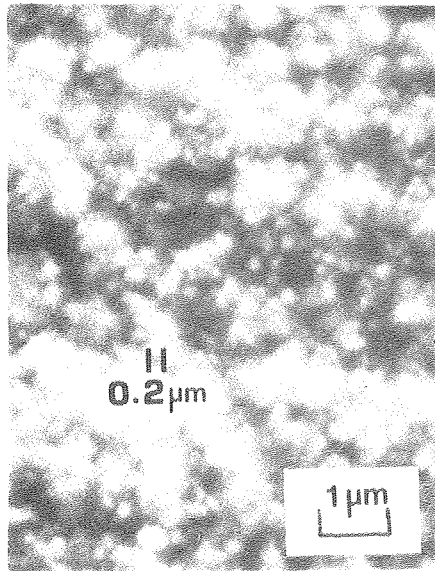


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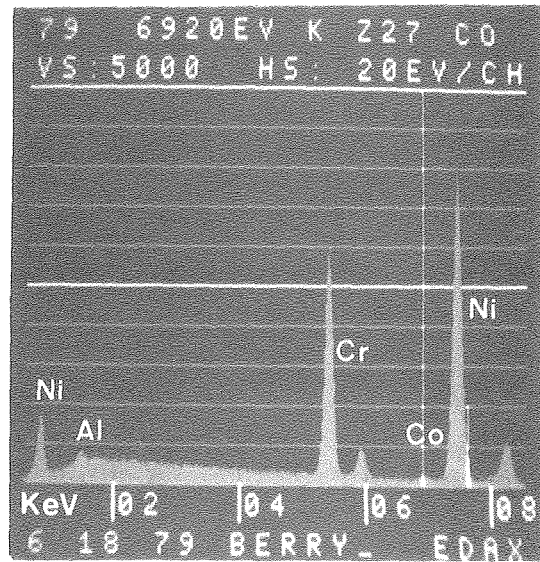
Fig. 1. Hemispherical Spectral Reflectance for Berry Solar Strip and Ergenics Maxorb selective surface. The Berry finish represents the typical reflectance for both foil and batch plated black chrome.



a



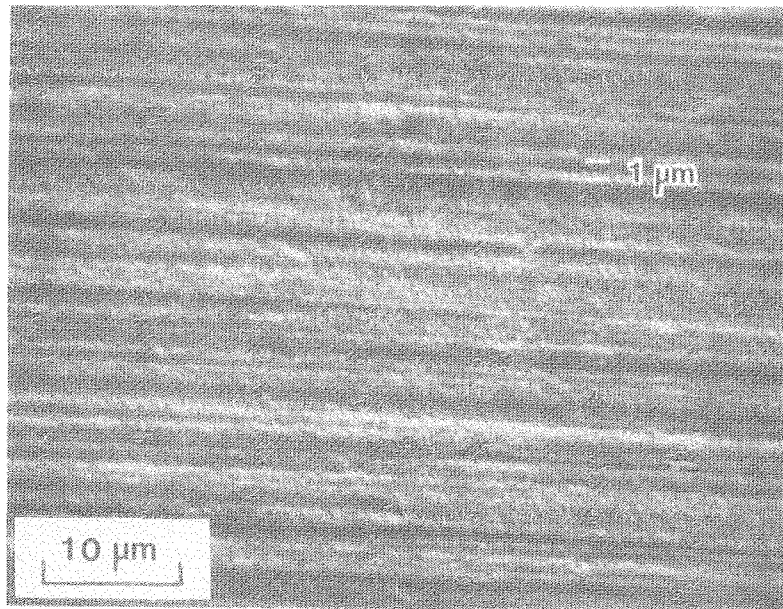
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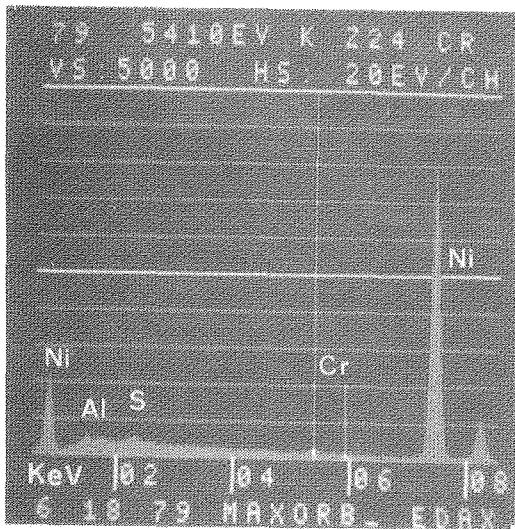
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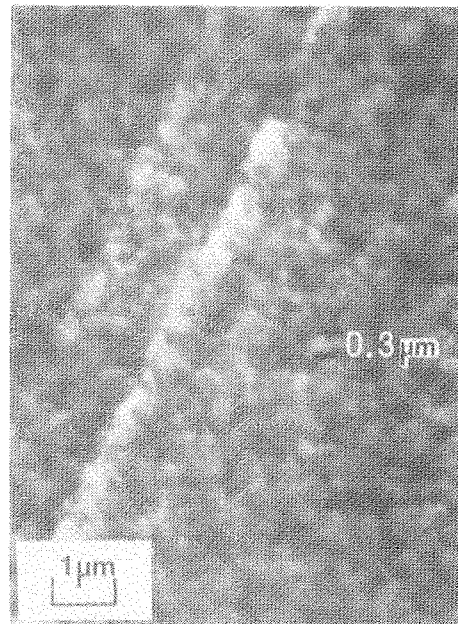
Fig. 2. Typical surface microstructure of Berry black chrome on nickel plated copper foil as seen by the scanning electron microscope at 20 kV (a) typical surface microstructure (d) details of particles (c) EDAX of region (b) showing chromium, nickel and trace of cobalt as principal constituents. The Aluminum peak is from the sample holder.



a



b



c

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Fig. 3. Typical surface microstructure of Ergenics Maxorb nickel foil as examined by the scanning electron microscope at 20 kV (a) typical surface (b) details of particulate surface (c) EDAX of region b, showing nickel and a trace of sulfur and chromium as principal constituents the aluminum peak is from the sample holder.

Research and Development of New Solar Foils

Two studies which are publicly known are the development project at the Optical Coating Laboratory, Inc. (OCLI), (Santa Rosa, Calif.) and the research study by Telic Corp. (Santa Monica, Calif.).

The OCLI foil is a vacuum deposited multilayer absorber on metal. A temperature resistance adhesive has also been specially developed for use with this solar foil. Currently this foil is in the evaluation stage. It is expected to be available this year.

Telic is presently involved with the development of methods for production of low cost selective absorbers on pipes and continuous coating of foils. The specific technique involves reactive sputter deposition with cylindrical magnetron source. Sputtered coatings like Cr-Cr₂O₃ codeposit, (a type of black chrome) and the AMA coating, Al₂O₃-Mo-Al₂O₃, a high temperature absorber, can be created in this manner.

In cylindrical magnetron sputtering the workpiece (foil) serves as the cathode of a low pressure glow discharge, the source of ions for sputtering. Sputtering is essentially a physical process of knocking atoms or molecules out of a source material with ions and subsequently depositing these atoms or molecules on a substrate under vacuum. Reactive gases can be used also to form desired compounds such as oxides. The purpose of the magnetron is to provide a ion rich plasma to permit coatings to be deposited over large work areas at acceptable deposition rates. A schematic cross-section of this device for foil deposition is shown in Fig. 4. (6).

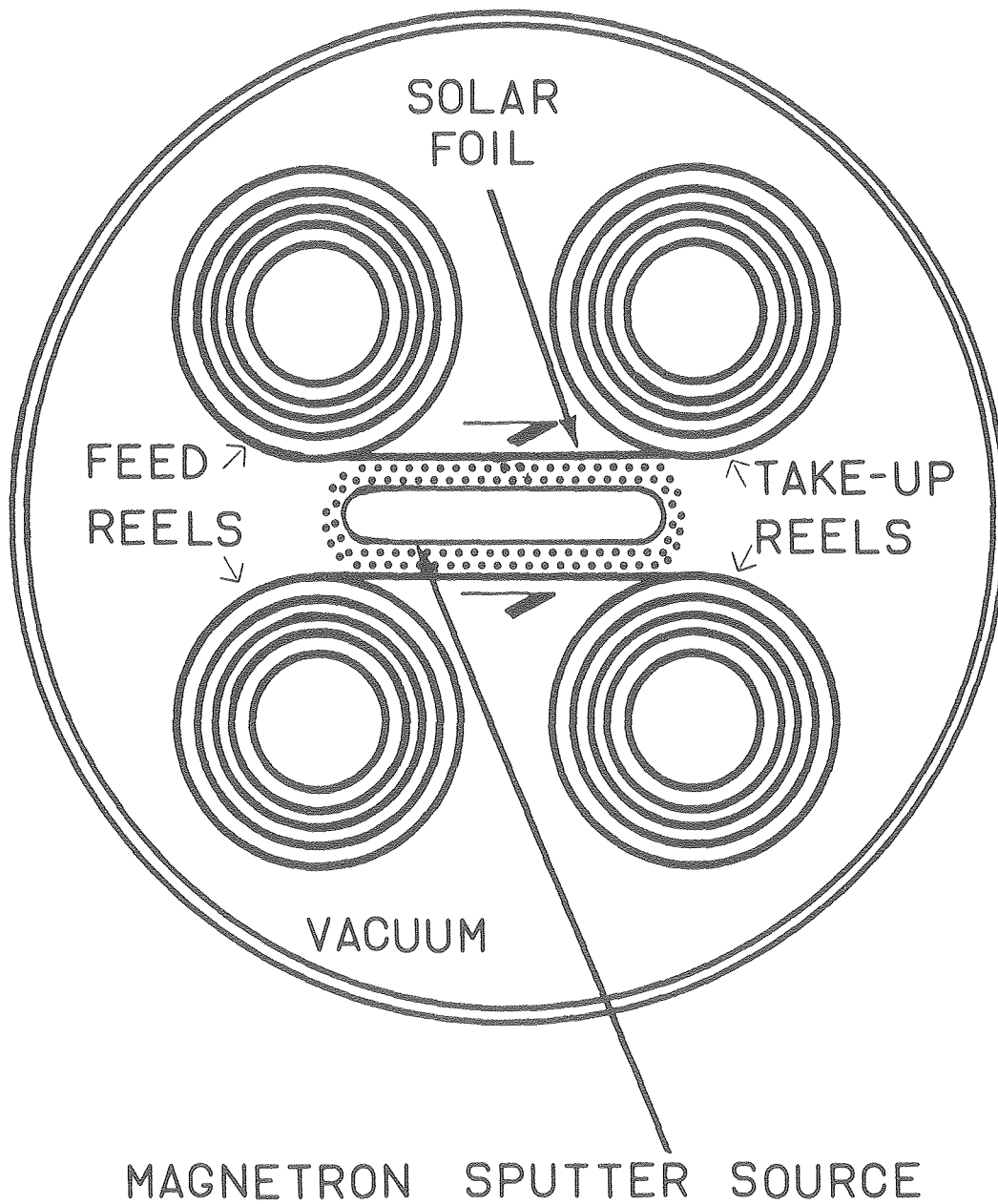
As a result of a recent Telic study (7) it was found that a 304 - stainless steel/oxide could be sputtered which has properties similar to the Cr-Cr₂O₃ coating, at quite a cost savings. The stainless steel cermet has yielded $a_s = 0.89$ and $e_{iR,H} = 0.07$.

Finally, it must be noted that the continuous coating of foils by cylindrical magnetron sputtering has not been demonstrated as yet, but the potential is there, along with quite a wide range of possible coating compositions.

Another process for the production of black chrome on aluminum foil was noted a few years ago (8). This process consisted of zincating the aluminum foil, after which a copper flash was deposited. On top of the flash a 13 micron (0.0005 in.) layer of nickel was deposited along with a top layer of black chrome.

Thick Foils for Direct Fabrication of Solar Collectors

Absorber coated thick foils or strips can be continuously plated much like thin foils. Berry Solar Products also produces "SolarStrip" with thicknesses of 0.25 mm (0.01 in.) and 0.3 mm (0.012 in.). It may be



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Fig. 4. Schematic cross section of a cylindrical magnetron sputtering apparatus (7). Shown is the continuous deposition of selective absorber coating on metal foil.

possible to coat aluminum strip up to 0.5 mm (0.02 in.), too. In addition, textured absorber strips which exhibit increased rigidity and surface area are available from Berry.

Only pipes, for liquid collectors, need to be bonded to the back of absorber strips to complete the manufacture of the collector plates. Due to the durability of Black chrome and presence of a protective quick-release coating, this strip can be easily punched, rolled, and formed into specific collector shapes. The pipes can be attached by a variety of methods including adhesive bonding, soldering, high frequency welding and mechanical fitting. Some of these methods do require proper heat sinking as black chrome does have a maximum temperature limit of about 350°C (662°F). Adhesives used for pipe bonding will also be covered in a subsequent section.

Bonding of Foils to Substrates

The method generally used here in applying the foil to the substrate is by rolling with a hard rubber roller. Hand methods are generally suggested, although an automated system could be devised. Gloves are used when applying the Maxorb surface as these protect the finish as well as protecting the handlers from cuts. Berry Solar Strip avoids this problem by using a protective polymer quick-release coating. For cylindrical pipes, foil can be bonded with a hot melted adhesive during wrapping.

Applications of Foil and Strip

Many of the uses for both foil and strip are obvious; a few diverse applications are noted here. Selective absorber foil is useful in solar passive architecture. It can be used for Trombe and tube walls not only to increase the wall and air temperature but at night serving as a poor radiator, thereby reducing the need or even eliminating it for night insulation (9). Foil can be spirally wound around pipes for concentrating collectors. Another advantage of foil is that it can be applied to many different materials, which otherwise could not be coated with black chrome. In air collectors, strip can be used either directly or textured for increased heat transfer.

Testing and Evaluation of Foils and Strip

Since metal foils and strip have only been used commercially recently, just short term testing has been performed.

Berry solar foil has been dynamically compared to a black painted absorber, using parallel collectors. Results showed that the Berry black chrome selective absorber realized a gain in heat flux extraction of 23-117% over that of the painted collector. These values must be used carefully because they do represent specific operating conditions and assumptions noted in Ref. 2.

The net effect of having a thin adhesive layer appears to be negligible. A specific case showed that in the presence of 50 microns (0.002 in.) of adhesive with a low adhesive conductivity of $0.073 \text{ w/m}^2 \text{ }^\circ\text{C}$, the fin efficiency declined only 1%, thereby resulting in a net decrease in collection efficiency of about 0.33%. To further substantiate such a claim, parallel testing should be performed for batch plated and foil coated collectors, using identical absorber types and materials.

Researchers at INCO have performed tests on Maxorb coated flat plate collectors, finding that it performs just as well as the black chrome batch plated collectors (10), as attested in Fig. 5. Maxorb has been tested for 140 days in 97% relative humidity at 92°C (200°F). After the test, no sign of deterioration was noted. Also, this surface was noted to be stable in air for 140 days up to 150°C (302°F).

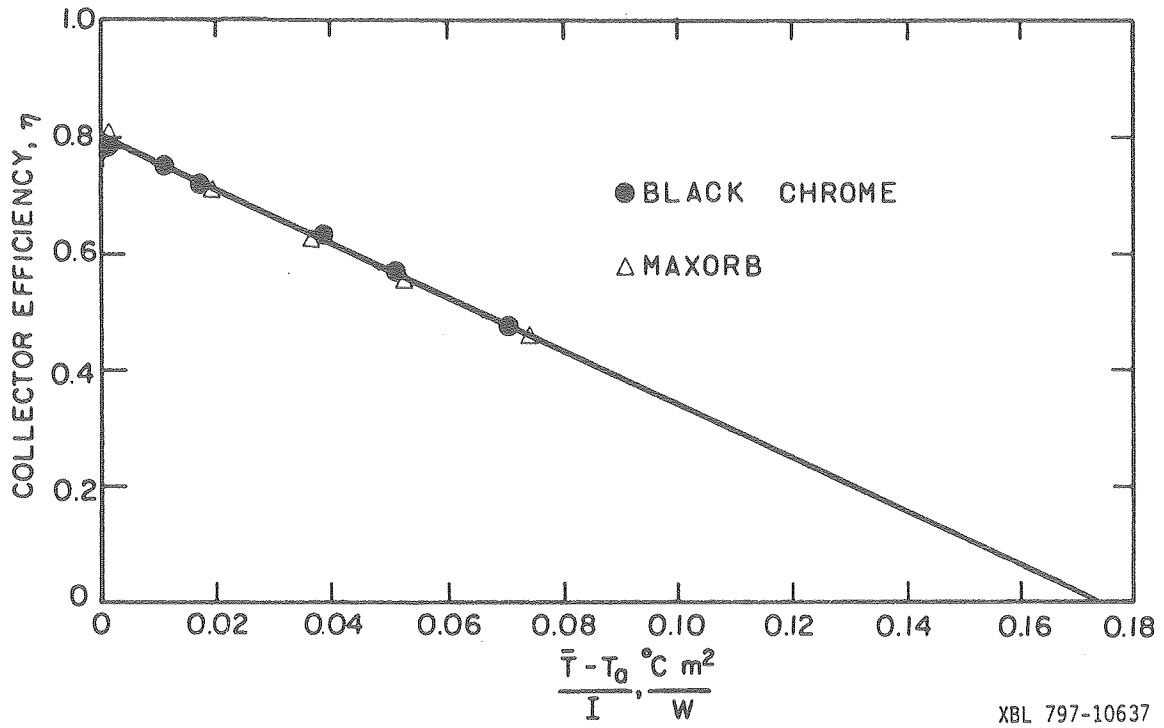
Preliminary results on Maxorb testing indicate that it is also stable to 200°C (292°F) for at least 56 days and stable for at least 14 days at 250°C (482°F), but beyond this temperature the adhesive is expected to break down.

ADHESIVES FOR ABSORBER PLATES

Attention should be directed to the two principal usages of adhesives: contact or thin film adhesives are necessary for bonding the foil to absorber plates and the thicker adhesives can be used for bonding absorber pipes to the plate surface. In each case different properties of adhesive media are required.

For the solar foils it has been calculated that nonconductive adhesive film should not exceed 127 microns (0.005 in.) for good thermal conduction (11) and be greater than 50 microns (.002 in) for proper adhesion (Ref. 5). The resulting laminate should be able to withstand continuous temperatures in excess of 120°C (250°F) and 232°C (450°F) under stagnation conditions. For the Maxorb surface it has been noted that for exposures up to 130°C (266°F) an adhesive peel strength of at least 35 Kg/m (1.96 lb/in) is required to prevent delamination (see Ref. 5). Peel strength is usually determined by the ASTM D-1000 method either for 90° or 180° pulling of the foil from the substrate. In Table 1 there are many types of prospective adhesives. If the peel strength of 35 Kg/m is a general requirement for all foils, then very few adhesives noted in Table I are acceptable. The other major consideration for selection is the cost of the adhesive and ease of application and curing. For foils, there has been success with Dow Corning 282 contact adhesive, for example.

Another application of adhesives is for bonding of pipes to collector plates. In these instances the bonding joints tend to be thicker than for the foils; usually a conductive sealant is necessary. Conductance of a bond joint depends directly upon adhesive conductivity, bond joint



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Fig. 5. Collector performance in terms of integrated instantaneous efficiency to the ratio of net temperature change above ambient ($\bar{T} - T_a$) and incident solar radiation (I). Data from Ref. (10).

TABLE 1. Adhesives for Bonding of Thin Absorber Foil to Solar Collectors

The adhesives listed in this table have been selected for use with solar foils. For a particular foil and collector design the suitability of a specific adhesive should be determined by the user. Manufacturers data has not been verified for accuracy.

Adhesive	Type	Max. Service Temperature °C	Cure @°C	Peel Strength kg/m (°C), 90°
<u>General Electric</u>				
SR 529	silicone resin	260	165-175°C	31.3(150)*
SR 573	silicone resin	260	20 sec @120 @20 psi	19.0(150)*
SR 574	silicone resin	260	---	9.4(150)*
<u>Dupont</u>				
Surlyn A	Thermoplastic ionomer film	260	220-232°C	8.9(176)
<u>Dow Corning</u>				
DC 280A/284	Silicone Rubber 60% Solids	250(316)	Min @150-200	44.6(176)
DC 282	Silicone Rubber 60% Solids	250(316)	Min @150-200	55.4(176)
<u>American Cyanamid</u>				
BR 34B-18	Polyimide 75% solids	250(360)	90 min @ 40 psi @ 285°C	
<u>3 M</u>				
Isotak Y9469	Acrylic pressure sens. tape	204(260)	None	39 (1976)
<u>National Starch</u>				
Duro-Tak 80-1047	Acrylic pressure sens. adh.	>176	2-3 min @ 121°C	-
Duro-Flex 25/28	Acrylic Moist. Cure adh.	-	-	-
<u>3 M**</u>				
2214 HT	Epoxy paste 100% solids + Al	149	40 min @121	36 (121)

Source Refs. (5), (11) and Manufacturers Data.

* 180° peel strength

** Epoxy may be too brittle for this application.

TABLE 2. Adhesives for Collector Pipe Bonding

The following list is a sampling of adhesives for absorber plate to pipe bonding. The specific suitability of a particular adhesive is left to the user. Manufacturers data has not been verified for accuracy.

Adhesive	Type	Maximum Service Temp. °C	Intermit. Service °C	Cure °C	Thermal Conductivity W/m°C
<u>Dow Corning</u>					
732 RTV	Silicone	260	316	12 hr. @RT	(0.173) 0.190
738 RTV	Silicone paste	260	316	72 hr. @RT	(0.175) 0.21
790 RTV	Silicone	260	316	7-14 days @RT	(0.19) 0.21
<u>General Electric</u>					
RTV 90	2 part Silicone	260	316	72 hr. @RT	(0.27) 0.31
RTV 116	Silicone	260	316	72 hr. @RT	0.21
RTV 156	Silicone	260	316	72 hr. @RT	0.21
RTV 580	2 part Silic.	260	316	72 hr. @RT	0.31
<u>Emerson & Cuming</u>					
Eccobond 276	100% solids Epoxy paste	232		121-176°C	1.38
Eccobond 281	Epoxy paste	205		121-176°C	1.44
<u>Castall</u>					
1200 HTC	Cond. Epoxy	205	300	24 hr. @RT	(0.73) 1.44
<u>Devcon</u>					
C1	Epoxy + 80% Al	204		1 hr. @204	(0.71) 1.28
<u>Castall</u>					
341	Cond. Epoxy	155	330	24 hr. RT	(0.87) 1.11
1520	Epoxy	155	330	24 hr. RT	(0.63) 1.38
<u>Hysol</u>					
EA 929	Epoxy	149		3-4 hr @126	(0.138) 0.346
EA 934	Epoxy	149		1 hr @126	(0.311) 0.346

For thermal conductivity quantity in parenthesis was measured by Ref. (12). For comparison, the thermal conductivity for copper is 385 W/m°C; steel is 47.6 W/m°C and water 0.6 W/m°C. Source after Ref. (12) and manufacturers product literature.

area, and interfacial resistance; also, it depends inversely upon joint thickness. The recommendation is that a bond joint have conductance greater than 30 W/m (32.5 BTU hr/ft). A recent study has resulted with recommended adhesives (12). These adhesives are outlined in part in Table 2. Adhesives which are poor electrical conductors have an added advantage of inhibiting galvanic corrosion, if dissimilar metals are used, such as bonding copper to aluminum.

COST ANALYSIS

A preliminary cost comparison is necessary to judge the relative competitiveness of adhesive foils with batch plating methods. The following prices are only for comparative use as their actual values change regularly. For isolated or unusual applications, the manufacturer should be consulted first. Then, too, these prices are not representative of very large scale production facilities.

Currently (October 1979), the cost of a thin absorber foil ranges from \$11-22/m² (\$1-2/ft²) in 10,000 ft² sizes dropping downward to small quantity orders. This price range can also include an adhesive, as seen with Maxsorb. The cost of black chrome including nickel-plated copper strip, which can be formed directly into absorbers, is \$18-23/m², (\$1.75 - 2.10 ft²) in the same quantities. The cost of black chrome plating alone is \$0.90/ft² for this process.

Batch black chrome plating with nickel, not including the collector cost, for flat collectors ranges from \$12 to \$27/m² (\$0.90 - 2.50+/ft²) for amounts ranging from 10,000 ft² to small quantities. Notice that these costs are comparable to foils but the expense of two-way shipping and packaging have not been included for the batch process. Also, it must be noted that there is a labor cost involved in applying the foil and again a one-way shipping charge to deliver the foil to the collector manufacturer. The convenience of having foil on the manufacturing site may also carry hidden advantages, such as faster production time and price stability. Without making an in-depth study, the overview seems to indicate that there could be a substantial savings advantage in using the coated strip for direct forming of solar collectors.

CONCLUSIONS

Solar selective foils can be produced successfully by a variety of methods including electrodeposition (Berry Solar), chemical conversion (Maxorb), vacuum deposition (OCLI) and by magnetron sputtering (Telic). The first two are commercial processes, marketing foil for roughly \$11-22/m² (1-2/ft²). Contact adhesives limit the upper temperature of these foils to about 250°C. In the case of black chrome this is significant, because it is stable to 350°C. But for most flat plate applications bonding adhesives are adequate. Low cost thinly conductive high temperature adhesives exist as a principle development area now.

When tested, foils such as Maxorb have shown no short range degradation below 200°C; long range testing is in progress. Berry black chrome exhibits similar properties as those of the batch plated black chrome. The foils are competitively priced in comparison with batch plated black chrome and offer some advantages such as savings on packaging and shipping, production turn around, no size limitations and versatility for different substrate materials. However, for a realistic comparison with the batch plated collectors, the foil coated collectors would have to exhibit the same lifetime and durability without significant increased costs during the foil bonding and handling operations. On the other hand, for low quantity custom solar collectors foils do have a cost savings over that of batch plating; this is mainly due to the relatively high cost of plating low quantity prototypes.

Another usage for foils is for the upgrading or replacing of aged or damaged solar collector absorber surfaces. This operation could be done on site in most cases without major disassembly of the collector. Also, foils can be applied to air collectors and passive solar designs.

An alternate process to be considered is the use of heavy coated foils as absorber strips for direct fabrication of solar collector plates. The only major processing procedure with this design consists of bonding the absorber tubes to the strips. The strip is available commercially from Berry, (priced from \$1.75 - 2.10) which represents a considerable costs saving over conventional collectors. Also, heavy strips can be used directly for solar air collectors.

The only developments which may stifle the increased use of foils and strip are the creation of adherent high temperature selective paints and significant cost reductions in the batch plating operations. On the other hand, new improvements in processing of selective foils such as a low cost reactive magnetron sputtering process may make foil very attractive from an economic standpoint.

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