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COATINGS FOR ENHANCED PHOTOTHERMAL ENERGY COLLECTION II

______Non-Selective and Energy Control Films.

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ABSTRACT

Several types of coatings and surface preparations, other than selective absorbers, can be utilized for economical collection and control of solar energy. These films can be used for both solar thermal collectors and for window systems in buildings. Numerous non-selective, hot and cold mirror, and antireflective coatings are reviewed and tabulated. Detailed reflectance, emittance and thermal stability data are presented for these various coatings. Both moderately selective and non-selective absorbers consist of black paint, chemical conversion finishes, electroplated and anodized coatings. Both hot and cold mirror coatings are selective transmitters of energy. They are considered for applications where light and heat need to be separated and trapped. Antireflective films are evaluated for use on glass surfaces. The findings of this study reveal many different types of inexpensive and promising coatings for efficient utilization of solar energy.

1. INTRODUCTION

Surface coatings play an important role in the utilization of solar energy for both commerical and domestic usage. To choose wisely such coatings as black absorbers and heat mirrors we need to know how different coatings perform, their potential application areas and projected costs.

In this study only a few particular coatings will be discussed in detail. Attention will be paid to both the research viewpoint and commercially available processes and finishes. Many of these commercial coatings are used presently for applications other than solar energy collection and control. The finishes to be discussed are non-selective black paints, chemical conversion finishes, electroplated coatings, heat mirrors, cold mirrors and antireflective films for glass. Current applications for non-selective black coatings are mainly for low temperature solar, water and air heaters. However, some refractory paints have very high temperature applications for solar furnaces and large solar boilers. Heat mirrors can play an important role when temperatures are required above 100°C, as radiative losses become significant. Heat mirrors also are used for temperature control in dwellings. The proposed application for cold mirrors is for passive control of greenhouse and dwelling temperatures. Antireflection films ordinarily are necessary for medium technology collectors in the realm of selective absorbers and heat mirrors.

The most popular optical parameters for these various coatings are absorptance (a) emittance (e), transmittance (t), and reflectance (r). Usually, values reported for a or e are integrated values derived from reflectance data. In general, many discrepancies and inaccuracies exist among the values reported, due mainly to different equipment and analytical procedures.

2. NON-SELECTIVE AND MODERATELY SELECTIVE COATINGS

This group of solar coatings certainly is the easiest to apply and probably the least expensive of all the collector coatings. The non-selective black coatings consist of paints, chemical conversion finishes or even electroplated surfaces, although some of the following coatings are classified as selective surfaces under specific manufacturing conditions.

There are many types of painted coatings. The list which follows this discussion will cover the properties of a few representative paint coatings. Ordinarily, high temperature and heat resistant black paints are used chiefly in industry as protective coatings for metals. In some cases specific colors are used for their heat control properties. Very few of these paints were formulated with solar energy collection in mind as this is an area of research just developing. Common pigments used to manufacture black paint are carbon black (0.02-0.09 microns) iron oxide Fe_3O_4 (0.5 microns), amorphous graphite, bone black (325 mesh) and asphalt bases noted by Bolz and Tuve [1].

Degradation properties in terms of solar spectral response (emittance, absorptance) with varying time or temperature, are little known. In many cases the spectral responses indicated should be viewed with caution, for they may represent somewhat ideal conditions and uncertain accuracy. When typical paints are applied to collector surfaces they will exhibit spectral responses quite different from that of the controlled thickness coatings applied to carefully polished metal surfaces.

Depicted in Fig. 1 are reflectance curves for fairly common black paints. Most of these are available as spray paints and do not require curing by baking, although certain types of 3M Black Velvet require it. Both Sherwin-Williams and Krylon paints can withstand about 100°C operating temperatures, while the 3M paint withstands 150°C. It must be noted that the temperature ratings of all paints reviewed are mechanical adhesion ratings and are not to be viewed in terms of optical degradation; that is, optical degradation may take place at even lower temperatures. The infrared absorptions noted in Fig. 1 are due to inherent absorptions in the paint binder. Higher temperature paints are shown in Fig. 2. The Cal Custom paint is a coating consisting of iron oxide pigment in a silicon binder; the absorption in the infrared is caused by this binder. The Parsons paints are lower temperature paints shown for comparison. The Cr_2O_3 paint has a dense black stain added to a normally green pigmented paint. This particular paint shows some selectivity. Various painted coatings in terms of their operating temperatures and characteristics are shown in Table 1. This tabulation is meant only to represent potential coatings and the actual feasibility of a particular coating for a solar application is still unknown in most cases.

Chemical conversion coatings exhibit the potential for low cost collector coatings and some coatings tabulated in Table 1 show moderate solar selectivity. Chemical conversion consists of dipping a metallic surface into a strong oxidizer or sulfidizer which subsequently forms an oxide or sulfide coating on the metallic base. Usually, this surface is integral with the base metal, which is different from a painted or electrodeposited surface. The mechanical properties of the surface can be quite different from those of the substrate, though. Drawbacks with most of the conversion coating baths are both temperature and safety. Many processes are run at 100-150^{o}C and are very corrosive. The Birchwood Casey coatings, on the other hand, are safe enough to apply by hand at room temperature. Also, most conversion coatings for zinc operate near room temperature. Zinc conversion may be in question since zinc is known to form a white corrosion product readily, according to Poll [5]. The advantages of chemical conversion are numerous: the coating is easily formed in a matter of minutes, the process is potentially inexpensive and there are many kinds of coatings available for steel (including stainless), copper and aluminum.

In Table 3 a summary of potential non-selective and moderately selective coatings is shown. Only coatings with published a and e values are represented in the table.

Overall, both painted and chemical conversion coatings are very attractive because so many potential processes exist, they are fairly easy and inexpensive to apply. The equipment to apply these coatings already exists and the coatings are currently used for many commercial items. These coatings do have a potential to be selective absorbers. The painted coatings need a binder which is highly transparent or poorly emitting in the infrared wavelengths. The binder should not suffer from infrared absorptions and must withstand fairly high temperatures (at least 150-200^{o}C). The conversion coatings need to be optimized and formed in such a way that they exhibit low infrared emittance. All of these coatings need to be evaluated in terms of stability and lifetime with temperature cycling and the collector environment.

3. COLD MIRROR COATINGS

A basic cold mirror coating reflects the visible and ultraviolet radiation in the solar spectrum while becoming a poor reflector but good transmitter of infrared wavelengths. The transmittance and reflectance for an ideal cold mirror coating is shown in Fig. 3. Included in this figure is a commercial coating made by OCLI [6] for this particular purpose. This OCLI coating is a multilayer thin film broad band reflector produced by vacuum deposition. The multilayer film consists of a thin metal base overlayed with several thin dielectric layers. An interesting application for this coating is a combined thermal-photovoltaic system. In this hypothetical system high energy visible light could be separated from the lower energy infrared, unusable for photovoltaic generation but very useful for photothermal heating of fluids. The photovoltaic cell would also run cooler in the absence of the infrared energy. With such a system a more efficient and sensible use of the various energies of the solar spectrum would result.

Another application of cold mirror coatings is for greenhouses; greenhouses consume annually 35×10^{12} btu of energy, much in the form of natural gas according to Winegarner [7]. Plants use particular wavelengths of light in the visible region for photosynthesis. Plants only utilize wavelengths less than 0.75 microns, after Winegarner [8]. The remaining amount of energy in the solar spectrum is available as heat for the greenhouse. By use of cold mirror coating as shown in Fig. 4 and a baffle type greenhouse roof, photosynthetic energy can be reflected into the greenhouse while infrared energy is transmitted into air channels. Within these channels there would be air flowing across absorber surfaces. The resulting hot air could be used for heating of the greenhouse and rock storage system. In this way the crops receive the solar energy wavelengths needed for growth while allowing the grower to maintain fairly stable daily greenhouse temperatures by simple heat management of the storage systems.

4. HEAT MIRROR COATINGS

Heat mirror coatings are also called transmitting selective surfaces which consist of single or multilayer films. These films transmit the solar visible and ultraviolet wavelengths while exhibiting a high reflectance to infrared energy. The optical behavior of a heat mirror is directly opposite to that of a cold mirror. Heat mirror coatings fall into two categories: Semitransparent metal, conducting microgrids, semiconductor single and multilayer types.

Heat mirror coatings can be made by a variety of methods. One rather simple technique consists of a spray and bake coating of fluorine doped stannic oxide (SnO_2), reported by Meinel and Meinel [9]. The more complicated tandem and multilayer films are deposited by sputtering and vacuum evaporation. Successful sputtered coatings include tin doped indium oxide (In_2O_3) single layer and $TiO_2/Ag/TiO_2$ multilayer films made by Fan and Bechner [10]. Intrinsic materials such as doped indium oxide, doped stannic oxide (SnO_2) and lanthanum hexaboride (La_2B_6) developed by Kauer [11], exhibit a natural transmitting solar selectivity. However, this type of selectivity is not to be confused with that of a selective absorber, which exhibits high visible absorption. Other types of popular coatings include the metal/oxide heat mirrors; these have been successfully applied to plastics and glass and have applications for dwelling window systems. The most promising tandem coatings are gold-titanium oxide on plastic, reported by Levin and Schumacher [12], and copper or silver--silicon dioxide for both glass and plastic substrates as reported by King [13].

In Table 4, a tabulation of pertinent optical properties of selected heat mirror coatings is shown for reference. Also in Figs. 5-6, the spectral transmittance-reflectance properties of heat mirrors are depicted, including several important commercial varieties. The major application for these coatings is for a performance much like a selective surface if a heat mirror is used in conjunction with a standard black absorbing surface in a solar collector. In this application, the heat mirror coating is applied to the inside surface of a single glass cover collector or to the top surface of the inside cover of a double glass cover. This coating easily passes the high energy visible radiation with little absorption to the underlying black absorber. The absorber reradiates infrared energy at its operative temperature back to the cover. This energy is trapped by the heat mirror coating because of its high reflectivity in the infrared wavelengths. The net result is to absorb the visible energy and to poorly emit in the infrared, very much like a selective absorber. Heat mirror coatings have an advantage over selective absorbers in that they can operate at much lower temperatures.

A simple application for a heat mirror coating is control of temperatures in large office buildings, particularly when the building design requires a lot of glass. Heat mirror coatings can control the amount of heat allowed to come in or escape from the office environment while maintaining illumination levels.

An interesting heat mirror effect can be obtained by suspending a fine conducting mesh below the cover plate of a solar collector. A 0.25 μm mesh would behave like an electromagnetic filter. This mesh would appear as a transmitting material in the high energy visible while performing as an infrared reflector. Incorporating this mesh into a collector would mean that reradiated infrared energy from the absorber surface could be reflected back to it, thereby creating a drop in the net thermodynamic driving force for energy lost by the absorber, increasing collection efficiency.

5. ANTIREFLECTION COATINGS

Coatings can be used to control the surface reflections that occur every time electromagnetic radiation passes from one medium to another. For this discussion, the air-glass interface will be of primary importance, that is reflectance loss from collector covers. Antireflection films also are very important for the suppression of reflective losses associated with semiconductor surfaces such as with semiconductor-metal tandems and photovoltaics.

An antireflection coating can reduce the normal reflection loss of 4% by adding a quarter wavelength material of intermediate refractive index between air and glass. The effect of this coating is to cause destructive interference at the specified wavelength; nearby wavelengths are affected also by this film. The ideal coating for glass should have an index of refraction of 1.23, which is unfortunate because no suitable substance exists. A common optical coating is MgF_2 with $n = 1.38$. The spectral response of this coating, along with others, can be seen in Fig. 7. The MgF_2 coating reduces the reflectance to about 1.6% at 0.6 microns wavelength, which certainly is a significant improvement.

To get closer to the ideal coating, multilayer dielectric coatings are employed. Frequently, high index material is placed between the MgF_2 coating and glass to increase the effective index of glass; also, these layers can be used to broaden superior transmission properties over a wider spectrum. The use of intermediate coatings can be seen in Fig. 7 with the $MgF_2(n = 1.38)/CeO_2(n = 2.35)/CeF_2(n = 1.65)$ coating, studied by Meinel [9]. Also shown in this figure is one of OCLI's multilayer proprietary HEA coatings reported by Belber [9].

Another experimental material, where the purpose was to reduce reflective losses, is low index polymer coatings on glass. A coating of Teflon FEP dispersion (n = 1.34) appears to have promise according to Goldner and Haskal [20]. If Tedlar is used instead of glass, its transmittance can be increased by dipping in acetophenone.

Probably the least expensive treatment for glass is fluosilicic acid etch. This surface treatment, developed by Tomsen [21], primarily roughens by etching small pores, possibly in high calcium regions, leaving porous silica in the surface. This porous layer has cavities which are small with respect to the wavelength of light (200Å) giving this layer an effective refractive index less than that of solid glass, according to Jurisson [22]. The spectral properties are shown in Fig. 17 for this etching technique. Refinements of the fluosilicic procedure consists of two layer treatments.

Both single dip coatings, antireflection and etching, appear to be the least expensive for the collector cover applications, while the best performing coatings are the multilayer coatings. However, it appears that all the various antireflection coatings need to be evaluated and compared in terms of atmospheric and operational degradation.

6. APPLICATIONS OF COATINGS

Generally cost, efficiency and durability are key factors considered in solar energy utilization, although durability is sometimes overlooked. In the following, applications and comparative analysis of various coatings will be discussed. It is assumed that all coatings are quite stable and durable, though this may be far from some actual situations.

Two cases will be discussed: a standard double glazed flat plate collector operating at $93^{o}C$ ($200^{o}F$) with $21^{o}C$ ($70^{o}F$) ambient, and a parabolic concentrating collector operating at $315^{o}C$ ($600^{o}F$) with the same ambient temperature. In each case gains in efficiency will be evaluated for the contribution of a particular surface coating. For all cases presented sufficient solar energy is available to maintain a fixed fluid temperature. The only variable in the system is the coating. In this manner gains in efficiency can be correlated directly to the coatings used.

A flat plate collector at steady state is depicted in Fig. 8. The effects of using antireflective coatings and heat mirrors are evaluated with respect to a standard non-selective absorber. The largest gain in efficiency (9.9%) is obtained when a heat mirror is added to the third glass surface. This efficiency gain rivals the selective absorber ($a = 0.9$, $e = 0.1$) which would realize a 12.5% gain.

A parabolic collector is shown in Fig. 9. By addition of a single surface antireflection coating a minor increase of 2.1% is noted in efficiency.

Whether or not such coatings would actually be used for a specific collector design would depend upon their particular cost effectiveness and benefits. That is, simple models such as the ones presented show the relative merit of using particular coatings but give no indication of the economics of their usage.

7. CONCLUSIONS

There are many non-selective paints and conversion coatings commonly used in industry for both large and small routine applications. In spite of this, very little is known about these coatings for solar energy applications. Refractory paints such as Pyromark which can withstand temperatures in excess of 1300°C. Many of these coatings are inexpensive and can be as low as $\$0.22/m^2$ and inherently simple to apply in contrast to others which require special safety precautions and boiling temperatures. Some very basic testing of these coatings needs to be done to determine humidity and corrosion resistance, degradation under ultraviolet light, and most important, thermal stability in terms of optical properties rather than just mechanical adhesion ratings.

Finally, an area of important innovation is the development of a high temperature binder, possibly a modified silicone, which would appear transparent in the infrared wavelengths. With use of such a binder it would be possible to develop a selective paint.

For oxide and sulfide coatings formed from chemical conversion, it is important that these coatings withstand the effects of thermal cycling and be able to protect the substrate from corrosion.

Hot and cold mirrors should be considered in the realm of selective absorbers. These special coatings have the ability to separate heat and light, that is, their application is best suited for photovoltaic/combined thermal systems, as energy control coatings for residential and commercial windows. Heat mirrors also rival the selective surface as long as low convective losses are maintained. Their durability and cost effectiveness remain and key factors in their development and use.

Antireflection coatings range from precision multilayer films to dip etched surface roughening. Since these coatings add only a mirror improvement in efficiency they may have applications only for large concentrating collectors. However, the dip etch techniques appear to be cost effective enough for most applications. But again, as with the other coatings, extensive evaluation is needed before these coatings could be placed in widespread usage. In a closing note about the heat mirror and antireflection coatings, it is quite possible that these coatings can be applied in a continuous fashion during the glass making process.

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Table 1. Black Paint Coatings. All data taken from manufacturers' product literature; accuracy or completeness has not been verified.

Trade Name	Manufacturer	Highest Operating Temp. °C	Type
Pyromark 2800	Tempil	1371	iron oxide + silicone
Novamet 150	Ergenics	815	inorganic pig. waterbase
Black Paint	Exxon	>700	silicone + silicate base
VHT Flameproof SP 102	Sperex	650 (815)	inorganic pig. + mod. silicone
Heat/Proof Coating 8029	Cal Custom/Hawk	649	iron oxide + mod. silicone
G-3113 HT Black	Ball	649	-
Inorganic Paint	Martin Marietta	>550	-
S-31 Black Paint	Rockwell	>550	-
Thurmalox 270	Dampney	537 (615)	silicone base
Pyromark 800	Tempil	427	silicone polyester base
4279 Heat Resist. Black	Rust-Oleum	427	carbon + silicone-alkyd
G-3858 HT Black	Ball	315	-
Stack Paint B68	Sherwin-Williams	260	-
Syncryl Enamel	Mass & Wahlstein	232	pigment + acrylic base
37J-4 Paint	Mobil	204	gilsonite + oil
719 Heat Resist.	Gavlon	204	silicone acrylic base
5779 Midnight Black	Rust-Oleum	177	carbon + acrylic emulsion

Table 1, contd.

Trade Nmae	Manufacturer	Highest Operating Temp. °C	Type
Durachem	Mass & Wahlstein	177	epoxy base
Nextel Black Velvet	3M	149	carbon + SiO_2
Black Paint	Parsons	130	-
412 Flat Black	Rust-Oleum	121 (177)	carbon + oil-alkyd base

Note: Temperatures in ( ) are for short time temperature resistance.

Table 2. Selected black conversion coatings. All data is taken from manufacturer's product literature, accuracy or completeness has not been verified.

Manufacturer and Trade Name	Type	Temp. & Time	Deposit Characteristics
Allied-Kelite: (Des Plaines, IL)			
Key Kote 70 Blackening Agent	Zinc Phosphate for Ferrous metals	21-38^{o}C at 0.5-4 min	
Birchwood Casey (Eden Prairie, MN)			
Presto Black	Cold Conversion Solution for ferrous metals	15-20^{o}C at 60 sec	Can be applied by hand, Non-Caustic
Aluma Black	Cold Conversion for Aluminum	15-20^{o}C at 1-2 min	Can be applied by hand, Non-Caustic
Antique Black	Cold Conversion for Copper		
Zinc Black	Cold Conversion for Zinc		
Conversion Chemical Corp. (Rockville, CT)			
Kenvert ZB	Oxidizer for Zinc	88^{o}C at 1-2 min	
Kenvert 311	Oxidizer for Zinc	29^{o}C at 20-30 sec	
Du-Lite Chemicals (Middletown, CT)			
Du-Lite Black	Chemical Finish for Steel	138^{o}C at 5-15 min	

Table 2. Continued.

Manufacturer and Trade Name	Type	Temp. & Time	Deposit Characteristics
Du-Lite 3-0	Chemical Finish for Stainless Steel	120°C at minutes	
Du-Lite Cu Black	Copper Oxidizer	100°C at minutes	
Enequist Corp. (Brooklyn, NY)			
Ultrex Z-27	Acidic Solution for Zinc	30-49°C at 1-5 min	
Enthone: (West Haven, CT) Ebonol S-34	Caustic Oxidizer for Steel	140°C at 3-25 min	$Fe(FeO_2)_2$ 1-5 μm thick
Ebonol C	Caustic Oxidizer for Copper	100°C at 5-10 min	CuO (1.3-5-μm thick) Stable to 204°C
Ebonol Z-80	Mild Alkalizer for Zinc	38°C at 3-10 min	Metal oxide (1-2.5 μm thick) Stable to 170°C
Ebonol SS-48	Oxidizer Stainless Steel	127°C at 5-15 min	Oxide/sulfide 1.5-2.5 μm thick
Enthox ZB-992	Acidic Strong Oxidizer	21-32°C at 0.5-3 min	Chromate Conversion
Heatbath Corp. (Spring Field, MA)			
Nickel Penetrate	Steel Alkaline Oxidizer with Nickel	143°C at minutes	Fe_3O_4 at 0.0001"thick oxide

Table 2. Continued.

Manufacturer and Trade Name	Type	Temp. & Time	Deposit Characteristics
A. F. Holden Co. (Milford, MI)			
Permablack	For Ferrous Metals	115-121°C at 5-15 min	Black Oxide
Lustre Black	For Ferrous Metals	140°C at 15-30 min	Iron Oxide Film
R. O. Hull Co. (Cleveland, Ohio)			
Roblack Zn-72	(0.002" + thickness	54-82°C at 3-8 min.	Mild corrosion protection
Roblack Zn	Mild acid oxidizer for zinc	21-66°C at 1-5 min	Mild corrosion protection
Roblack Fe	Strong alkali oxidizer for steel	138-149°C (boiling)	iron oxide 0.25 μm
Roblack Cu	Strong alkali oxidizer for copper	99-103°C at 5-15 min	copper oxide, corrosion resistant, etching needed for dull surface
IRCO Blackjack 53000	Acid conversion finish for steel	27-38°C at 0.25-1.5 min	matte black
Lubrizol (Cleveland, OH)			
IRCO Blackjack	Conversion Finish for Steel	27-34°C at minutes	matte black

Table 2. Continued.

Manufacturer and Trade Name	Type	Temp. & Time	Deposit Characteristics
Mitchell-Bradford (Milford, Conn.)	Alkaline oxidizer for aluminum	77-82°C	
Electroless Black Magic		0.5-10 min	
Turco Products (Carson, Calif.)	Alkaline oxidizer for steel	150°C	
Ferrotone			

Table 3. Summary of non-selective and moderately selective conversion coatings and paints for solar collectors. Only coatings with published a & e values are listed.

Manufacturer	Type	Solar Absorptance	IR Emittance
Conversion Coatings			
Alcoa	Alkaline Conversion	0.93	0.35
Ametek, Inc.	Electro. PbO_2 on Cu	0.98-0.99	0.30
Birchwood Casey	Acidic Conv. for Al.	0.96-0.97	0.55-0.73 (100°C)
Black Magic	Conversion Finish for Al.	0.82	0.12
Climax Moly.	(425°C) Dichromate Convers. for S. Steel	0.80	0.6 - 0.02
Enthone-Ebonol C	Alkaline Conversion for Cu.	0.84-0.95	0.06-0.40
Enthone-Ebonol S	Chemical Conversion for Steel	0.86	0.07
Enthone-Ebonol Z	Chemical Conversion for Zinc	0.75	0.13
Permaloy Corp.	Anodized Aluminum	0.94	0.71
Paints			
Bostik 436-3-8	Black Paint	0.90	0.92
Cal Custom/Hawk	Black Iron Oxide-Silicone Paint	0.95	0.83 (20°C)
Enersorb (De Soto)	Black Paint	0.97	0.92

Table 3, contd.

Manufacturer	Type	Solar Emittance (IR)	Absorptance
Exxon Black Paint	Silicone-Silicate base	0.98	0.9
Ferro Corp.	Black Porcelain Enamel	0.97-0.98	-
C. H. Hare 7729	Black Paint	0.96	0.90-0.92
Martin Marietta	Inorganic Paint	0.9-0.95	0.9-0.95
Nextel Black Velvet	Carbon black + SiO_2	0.96-0.98	0.89 (25°C)
Novamet 150	Waterbase inorganic enamel	0.96	0.84 (25°C)
Pyromark 2800	Iron oxide-silicone paint	0.87-0.90 (310-1100°C)	-
Rockwell S-31	Black Paint	0.8-0.85	0.8-0.85
Rust-Oleum	Black Paints (3)	0.95-0.96	0.87-0.90
Solarsorb (Caldwell Chemical)	Black Paint (C-1077)	0.9	0.6-0.8

Table 4. Optical properties of heat mirror coatings.

Type	Effective Transmission (Vis)	Effective Emittance (IR)	Reference
OCLI Indium Multilayer	0.84 (0.85)	0.14	[14, 8]
OCLI Silver Multilayer	0.72	0.17	[14]
MIT Sn doped In_2O_3 (RF Sputtered)	0.85(AM2)	0.081 (121°C)	[10]
MIT 180 TiO_2/180 Ag/180 T_iO_2 (RF Sputtered)	0.54(AM2)	0.071 (121°C)	[10]
MIT 330 TiO_2/130 g/330 TiO_2 (RF sputtered)	0.67	0.065 (25 C)	[15]
0.35 m Cd_2SnO_4/SiO_2 (sputtered)	0.78	~0.01 (150°C)	[16]
F doped SnO_2 (Solution baked)	0.75	0.07	[9]
		Reflectance (IR)	
MIT Sn doped IN_2O_3 (microgrid)	0.9	0.83	[17]
5% SnO_2 doped In_2O_3 (aerosol pyrolysis)	0.90	0.85	[18]
L_2B_6	0.85	0.90	[11]
Sierracin, Intrex + AR Au/TiO_x/plastic (Vac. Evap.)			
T42	0.78	0.72	[12]
T28	0.80	0.87	[12]

Table 4, contd.

Type	Effective Reflectance (Vis)	Refectance (IR)	Reference
Kinetic Coatings 52Å Cu/500Å SiO_2 (ion beam sputtering)	0.06 (1) 0.16 (2)	0.86 (3)	[13]
78Å Cu/500Å SiO_2	0.11 (1) 0.23 (2)	0.90 (3)	[13]
26Å Ag/500Å SiO_2	0.05 (1) 0.14 (2)	0.71 (4)	[13]
41Å Ag/500Å SiO_2	0.14 (1) 0.25 (2)	0.84 (3)	[13]

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(1) Integrated with respect to AM2 Solar Spectrum (0.4-0.7 μm)

(2) Integrated with respect to AM2 Solar Spectrum (0.35-2.5 μm)

(3) Average reflectance (4-50 μm)

(4) Average reflectance (5-10 μm)

Figure Captions

Fig. 1. Normal spectral reflectance for various black paints, measured at 40^{o}C. Presented in order are Sherwin Williams Enameloid Flat Black on aluminum substrate, Krylon Black No. 1602 on aluminum substrate, Touloukian [2]. 3M Nextel Black Velvet on aluminum, e = 0.93, Hogg and Smith [3].

Fig. 2. Hemispherical spectral reflectance at 30^{o}C for Cal Custom/ Hawk heat resistant coating on galvanized steel, Lampert [4]. Near normal spectral reflectance for Parsons' black paint on copper and black lacquer on brass and Cr_2O_3 pigmented (black stained) paint using NBS frit number 332, all at 25^{o}C. (Touloukian) [2].

Fig. 3. Spectral reflectance and transmittance for OCLI commercial cold mirror coating compared to the ideal mirror reflectance for a 0.95 m transition wavelength, OCLI [6].

Fig. 4. Spectral reflectance and transmittance for OCLI greenhouse cold mirror coating, Winegarner [7].

Fig. 5. Spectral transmittance and reflectance for various heat mirror coatings. The OCLI types are commercial coatings, Apfel [14]. The TiO_2-Ag coating is an MIT experimental coating, Fan and Bechner [10].

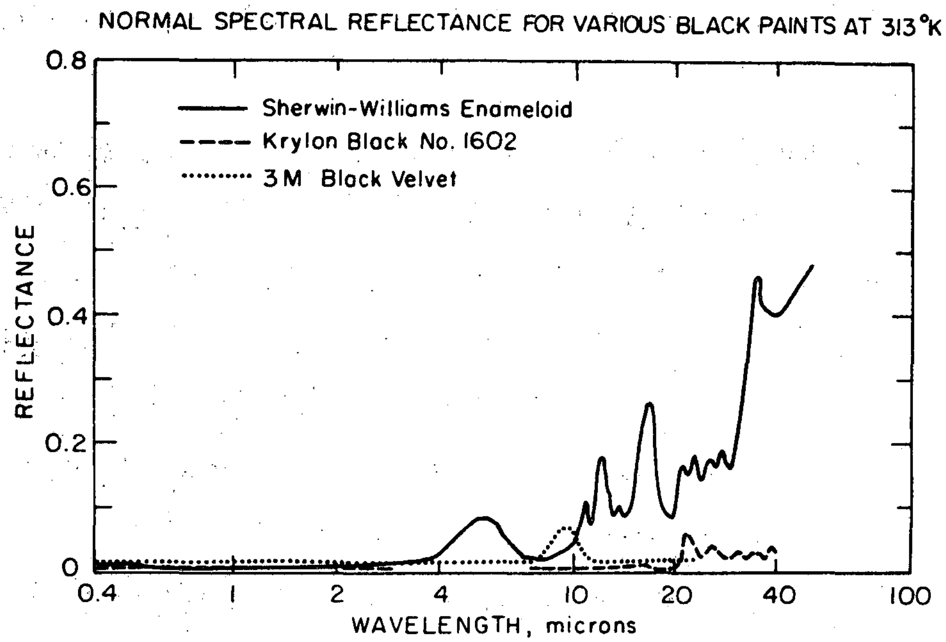
Fig. 6. Spectral transmittance and reflectance for three heat mirror coatings. The experimental Cd_2SnO_4/SiO_2 coating was developed by Haake [16] of MIT. The metal/SiO_2 heat mirrors were made by kinetic coatings, King [13].

Fig. 7. Reflectance of various antireflection coatings and treatments for glass. Coatings pictured are OCLI solar HEA film (Belber [19]), MgF_2 single and multilayer coatings reported by Meinel and Meinel [9] and an etching technique developed by Tomsen [21].

Fig. 8. The change in collection efficiency for a flat plate collector with a non-selective absorber (a = 0.92, e = 0.92, 93°C), operating at 93°C (200 F) with ambient temperature of 21°C (70°F), using various coatings (after Winegarner [7]). Notation: (R) Radiative loss, (C) Convective loss.

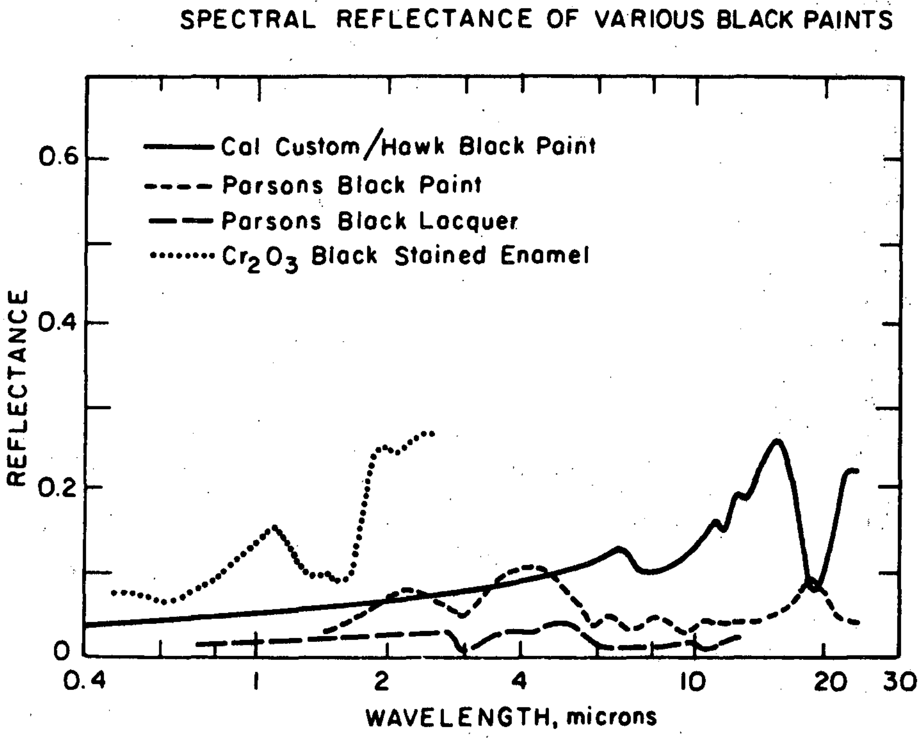
- (a) An increase of 6.3% efficiency is obtained by simply adding antireflection coatings.
- (b) Two heat mirror designs are noted (t = 0.85, e = 0.14). The third surface coating placement gives superior results.

Fig. 9. The effect of adding an antireflection coating to a parabolic concentrating collector with a non-selective absorber. The collector is operating at 315°C (600°F) with ambient temperature of 21°C (70°F) (after Winegarner [8]). Notation: (R) Net collection efficiency, (ΔR change in collection efficiency over that of a standard black absorber.



XBL 783-4705

Fig. 1.


SPECTRAL REFLECTANCE OF VARIOUS BLACK PAINTS

XBL 783-4716

Fig. 2.

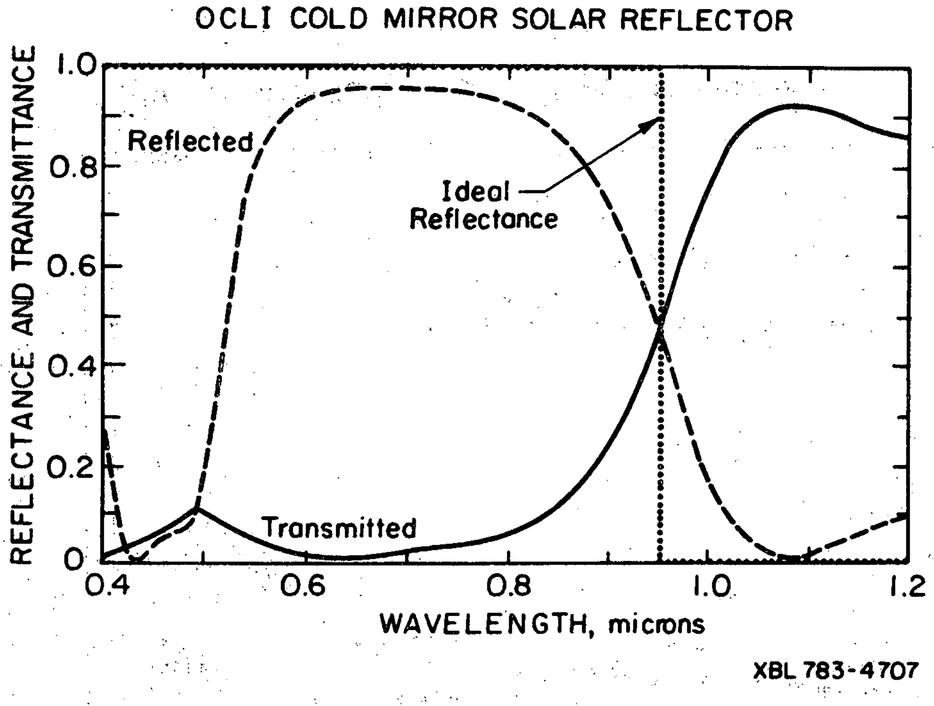

OCLI COLD MIRROR SOLAR REFLECTOR
REFLECTANCE AND TRANSMITTANCE
1.0
0.8
0.6
0.4
0.2
0
Reflected
Ideal
Reflectance
Transmitted
0.4
0.6
0.8
1.0
1.2
WAVELENGTH, microns
XBL 783-4707

Fig. 3.

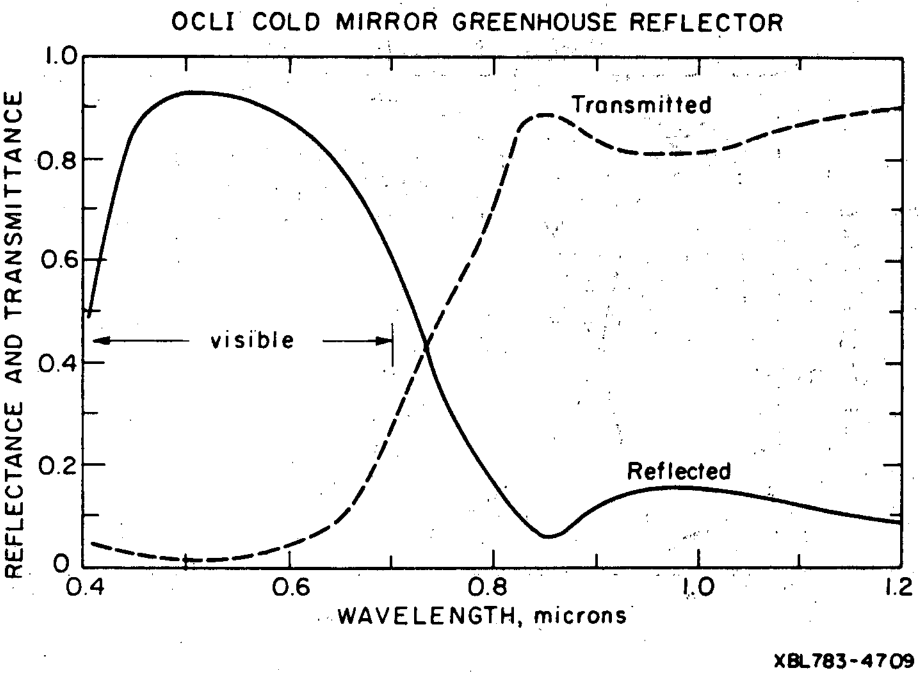

OCLI COLD MIRROR GREENHOUSE REFLECTOR
REFLECTANCE AND TRANSMITTANCE
1.0
0.8
0.6
0.4
0.2
0
0.4
0.6
0.8
1.0
1.2
WAVELENGTH, microns
Transmitted
Reflected
visible
XBL783-4709

Fig. 4.

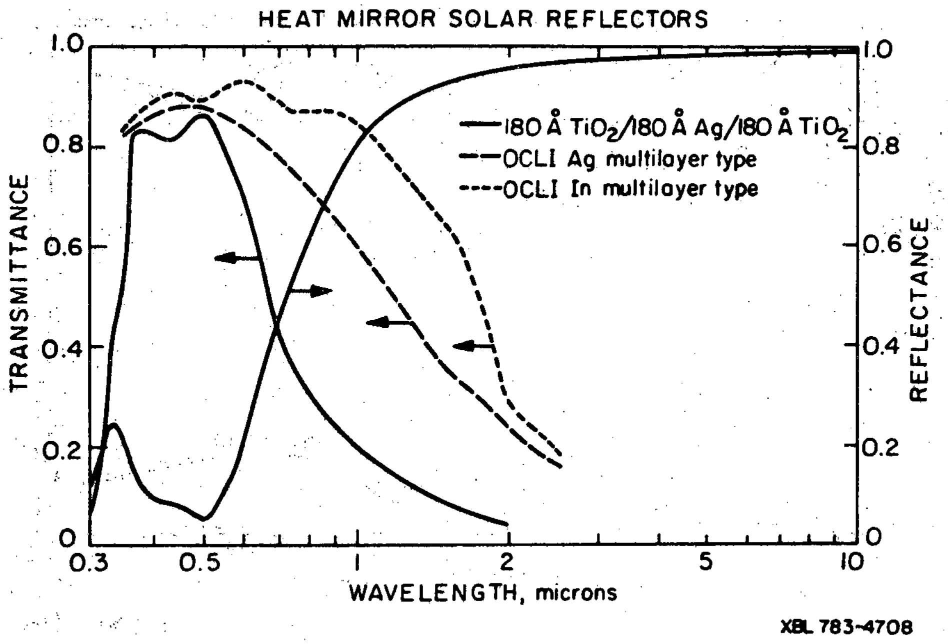

HEAT MIRROR SOLAR REFLECTORS
TRANSMITTANCE
REFLECTANCE
1.0
0.8
0.6
0.4
0.2
0
0.3
0.5
1
2
5
10
WAVELENGTH, microns
180 Å TiO_2/180 Å Ag/180 Å TiO_2
OCLI Ag multilayer type
OCLI In multilayer type
XBL 783-4708

Fig. 5.

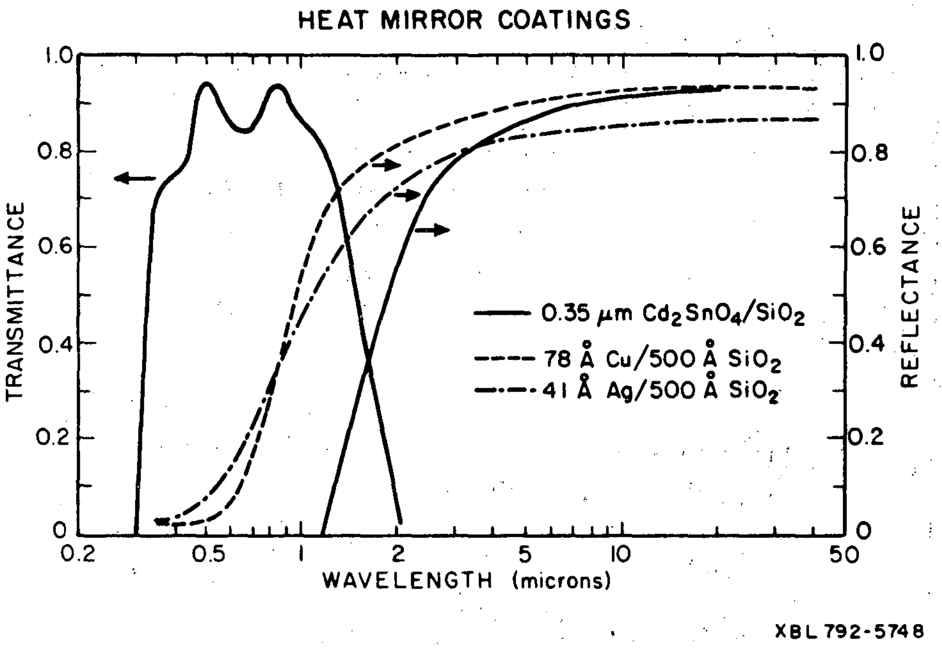
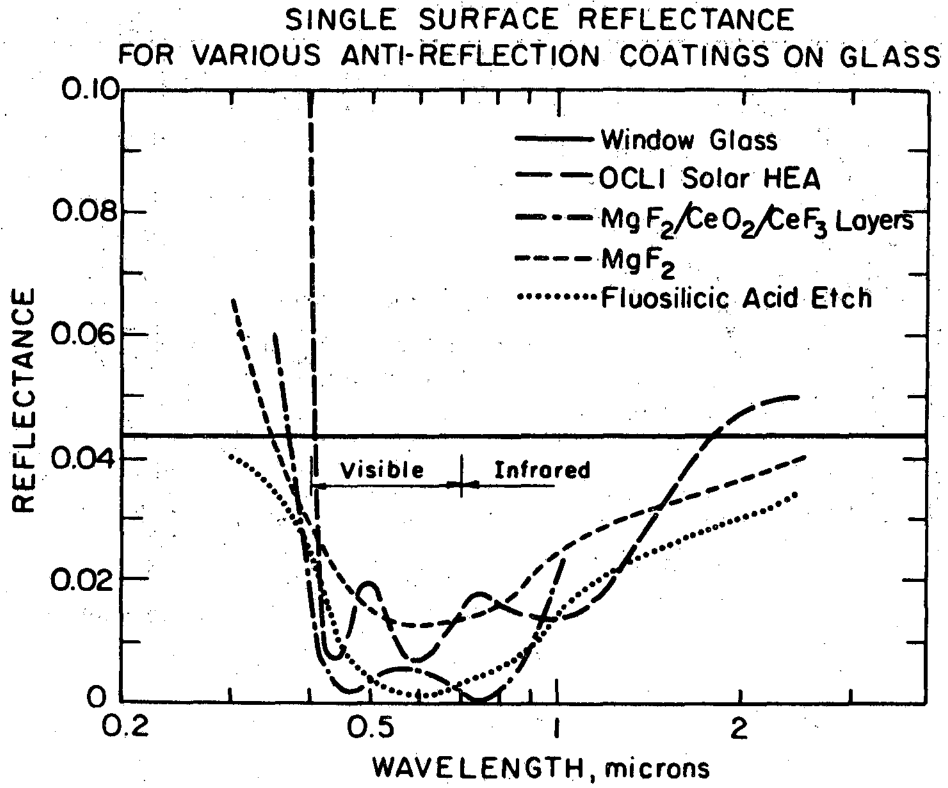
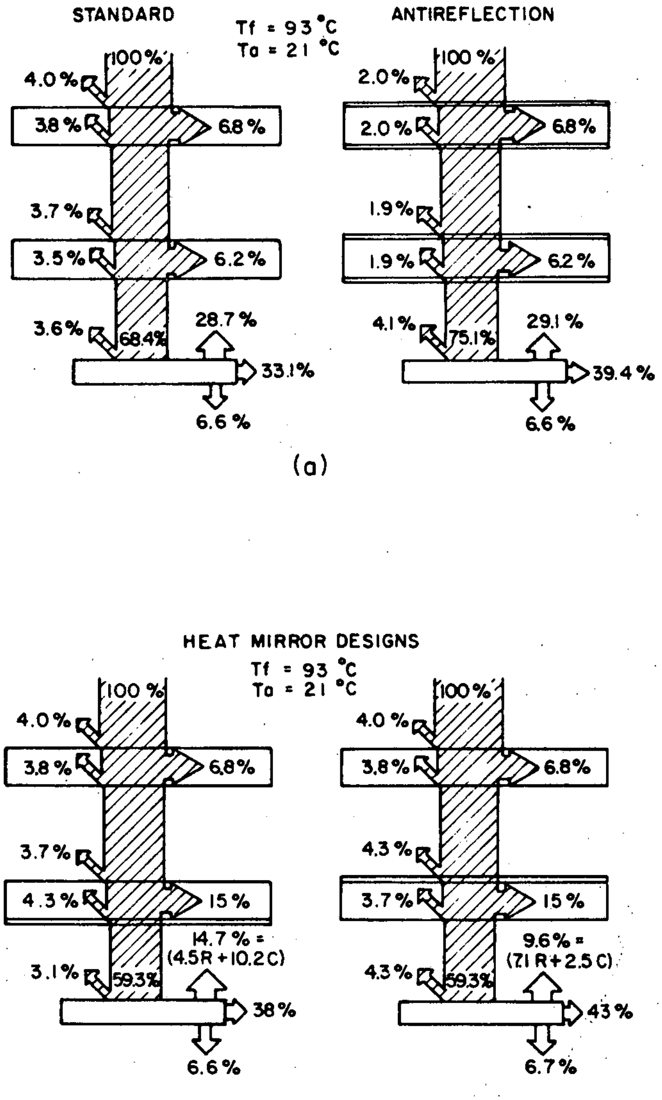

HEAT MIRROR COATINGS
TRANSMITTANCE
REFLECTANCE
WAVELENGTH (microns)
1.0
0.8
0.6
0.4
0.2
0
0.2
0.5
1
2
5
10
50
0.35 μm Cd₂SnO₄/SiO₂
78 Å Cu/500 Å SiO₂
41 Å Ag/500 Å SiO₂
XBL 792-5748

Fig. 6.



XBL 783- 4724

Fig. 7.

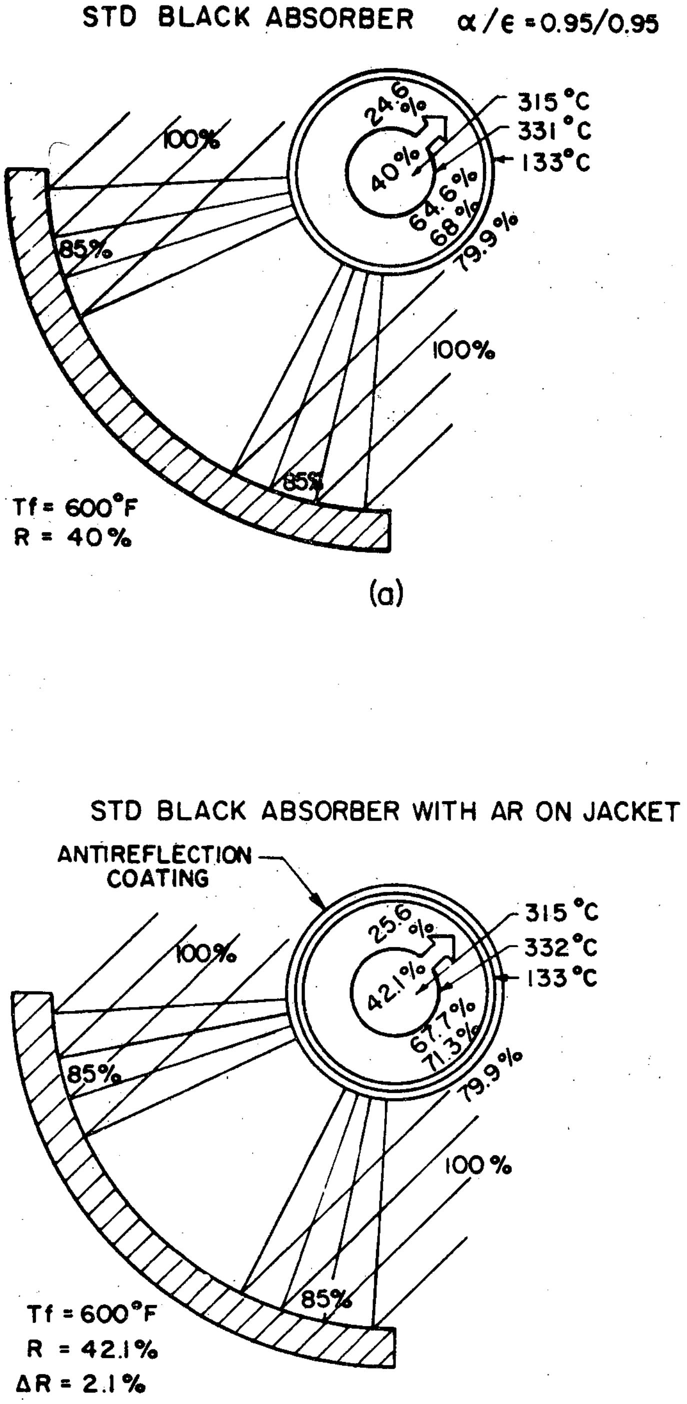


(a)

(b)

XBL 781-6856C

Fig. 8.



(a)

(b)

XBL 781-6857G

Fig. 9.

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