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OPTIMIZATION OF SOLAR-SELECTIVE PAINT COATINGS

FINAL REPORT

For the period 15 September 1980 – 15 June 1982

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Foreword

This is the final technical progress report describing the development of low-cost, high-performance, solar-selective paint coatings. The work was initiated at Honeywell in the Systems and Research Center by Dr. H.Y.B. Mar and in the Avionics Division by Mr. Paul B. Zimmer. Throughout the 9-year development history of this effort, various government agencies have provided support and direction, including the National Science Foundation (NSF), the Energy Research and Development Administration (ERDA), and, more recently, the United States Department of Energy (DOE). Each of these efforts has been guided by Mr. Zimmer with assistance from Dr. R.J.H. Lin, Mr. G.W. Nelson, Mr. W.D. McKelvey, and, most recently, by Mr. M.A. McChesney.

Special thanks and recognition is given to Mr. Gary W. Nelson who has steadfastly, faithfully, and patiently prepared, measured, and developed literally hundreds of experimental coatings during these 9 years and without whose outstanding contribution this effort would have been significantly more difficult if not impossible.

The current work was performed under contract DE-AC04-78CS14287, Mod 002, supported by the Solar Heating and Cooling Research and Development Branch, Office of Conservation and Solar Applications, U.S. Department of Energy, Los Alamos National Laboratory. This document attempts to both report the current work as well as integrate prior efforts by Honeywell to develop low-cost, high-performance, solar-selective paint coatings.

The authors gratefully acknowledge the guidance provided by Mr. Stanley W. Moore of Los Alamos National Laboratory, who is the Project Monitor.

Mr. Paul B. Zimmer is the Principal Investigator. The work was performed by M.A. McChesney, assisted by G.W. Nelson, W. Polec and R.J.H. Lin.

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Section 1
Introduction and Summary

The objective of this program was the development of low-cost, high-performance, solar-selective paint coatings for solar flat-plate collector (FPC) use and passive thermal wall application. Thickness-sensitive selective paint (TSSP) coating development was intended to demonstrate large-scale producibility. Thickness-insensitive selective paint (TISP) coating development was intended to develop and optimize the coating for passive solar systems and FPC applications.

SUMMARY

Low-cost, high-performance TSSP coatings and processes were developed to demonstrate large-scale producibility and meet all program goals. Dip, spray, roll, laminating and gravure processes were investigated and used to produce final samples. High-speed gravure coating was selected as the most promising process for solar foil fabrication. The foil was produced as a 10,000-ft^2 sample with optical properties of $\alpha_s = 0.90^1$ (0.93^2), and $\epsilon_{TH} = 0.15^3$ for the 28 pigment-volume concentration (PVC) F-6331/6247 silicone-epoxy coating, and $\alpha_s = 0.90$ and $\epsilon_{TH} = 0.07$ for the 28 PVC F-6331/SR-125 silicone coating. Total material and fabrication cost was \$0.24/ft^2, with \$0.15/ft^2 projected cost for 1 million ft^2. These costs include the protective film over the paint coating, paint-coating material, aluminum foil, adhesive, release liner, and the cost of fabrication.

Development and optimization of TISP coatings was not completely successful. A variation in reflective metal pigment was suspected of being the primary problem, although other variables may have contributed. Consistent repeating of optical properties of these coatings achieved on the previous program was not achieved. However, a new method of achieving better control of coating components was conceived and preliminary development initiated. The new concept was described as an engineered pigment approach.

The engineered pigment approach uses TSSP-coated metal foil particles instead of uncoated aluminum flakes in a liquid TSSP coating. The approach offers many advantages over the use of uncoated aluminum flakes: control of particle flatness, size, and thickness; control of the optical selectivity of each particle; and control of the liquid TSSP coating surrounding the coated particles. Unfortunately, this development came late in the program and could not be optimized. It does, however, promise the degree of control of coating ingredients needed to provide a truly thickness-insensitive selective paint coating.

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[1] Gier-Dunkle Model MS-251 reflectometer.

[2] Beckman DK-2A Spectrophotometer with integrating sphere.

[3] Gier-Dunkle Model DB-100 reflectometer.

Section 2

Thickness-Sensitive Selective Paint (TSSP) Development

This part of the program focused on the evaluation, development, and optimization of processes for the manufacture and application of thickness-sensitive selective paint coatings. The goal of this phase of the program was to demonstrate large-scale producibility for solar TSSP coatings. (Goals for this phase of development are summarized in Table 1.)

Table 1. Specific Objectives for Thickness-Sensitive Solar Paint

Objective	Plan
Optical	
α_s	0.93
ϵ_{TH}	0.10
Durability	
Mechanical	
Adhesion	Acceptable
Abrasion resistance	Acceptable
Environmental	
Accelerated weathering	Pass 20-year simulated exposure
Cycling humidity	Pass 10-day MIL-STD-810 exposure
Test site exposure	12 months
Reproducibility	
Solution stability	
Shelf life (minimum)	6 months
Application life	No appreciable settling in 8 hours
Application technique	
$\Delta\ \alpha_s$	0.02
$\Delta\ \epsilon_{TH}$	0.03
Scale-up	
Foil	10,000 ft^2
Panels	Ten, 3 ft × 6 ft
Cost (¢/ft^2)	
Material	1
Application	
Panel	3
Foil	2

CONCEPT

The optical properties of current solar-selective paint coatings depend on coating thickness and a low-emittance substrate for their selectivity. Ultra-thin paint coating films applied to reflective substrates that absorb solar energy but are semi-transparent in the infrared, have a "show-through." Thus, they provide the desired solar absorptance and low emittance. The control of coating thickness control throughout the development of solar-selective paint coatings was accomplished by dip-coating techniques. This precise technique uses the withdrawal rate of the substrate from the coating solution, coating solids, and coating PVC to control the coating thickness.

Coating thickness was prohibitively expensive to measure because it was beyond the capabilities of currently available eddy current thickness measuring equipment. Coating thickness could have been determined by other, more expensive techniques, including microsectioning/metallography, light shadowing, or the use of the scanning electron microscope (SEM).

While currently available eddy current thickness testers fail to measure accurately below 0.1 mil ($2.5\mu m$), light shadow and SEM techniques provided thickness values for a typical 30 PVC F-6631/SR-125 coating dip-coated at 2 in/min of 0.086 ($2.16\mu m$) and 0.088 mils ($2.24\mu m$), respectively. The average thickness for this coating was then estimated to be 0.087 mils ($2.21\mu m$).

The dip-coating process was used for maintaining base line information and is considered a viable procedure for small- to medium-size factories for producing solar-selective paint-coated sheet stock or collector panels. However, the goal of the current effort was to demonstrate the feasibility of a high-speed, high-volume, low-cost, solar-selective coating process. Gravure coating, electrostatic spray coating, and conventional spray coating techniques were investigated. The most promising procedures were developed and refined to the point of demonstrating high-volume production feasibility.

COATING PREPARATION

Experimental solar-selective paint coatings were formulated using conventional paint coating techniques. Appropriate quantities of pigment and binder were combined with solvent to achieve the desired PVC. As in previous programs, the mixtures were ball-milled using high-density aluminum oxide (Al_2O_3) grinding media in polyethylene containers to minimize contamination. During milling, pigment agglomerates were reduced to smaller agglomerates and discrete particles. The pigment agglomerate breakdown was monitored periodically during the several days of milling by measuring the relative particle dispersion or "grind" of the paint coating solution. Ball milling was used throughout the program as the standard preparation method. The paint industry has converted much of its processing of paint coatings from ball milling to sand milling. Ball milling takes a long time and is expensive due to the time required and the cleanup involved. Sand milling is as effective as ball milling in paint milling, and requires only a few hours to accomplish the same results that required several days in a ball mill. During this program, the method of paint preparation switched from ball milling to sand milling. Large batches of paint were sand-milled, with the exception of some used for the first run on the gravure coater.

OPTICAL PROPERTIES

Milled paint coating solutions were then applied to acetone-cleaned aluminum substrates, cured, and measured for optical properties. Solar absorptance (α_s) was measured with a Gier-Dunkle MS-251 solar reflectometer and emittance (ϵ_{TH}) with a Gier-Dunkle DB-100 infrared reflectometer without a filter to provide emittance values at 100°C. The Gier-Dunkle MS-251 reads 0.03 to 0.04 lower than the Beckman DK-2A spectrophotometer with an integrating sphere.

SOLAR PAINT COATING MATERIALS

Prior development of TSSP coatings made use of a number of pigment-binder systems. Some of the most promising coatings were simple combinations of Ferro F-6331 (FeMnCuOx) pigment and General Electric SR-125 silicone binder. Pigment-volume concentration (PVC) and coating solids were found to be among critical parameters for applying ultra-thin films to low-emitting substrates to achieve selectivity. Later, Honeywell discovered and developed rudimentary thickness-insensitive selective paint (TISP) coatings using aluminum flake directly in the coating as the low-emitting substrate. This showed the need to have a binder that cured at room ambient temperatures. It was also desirable to have an alternate pigment and binder available as backup materials. Thus, both pigments and binders required further investigation.

Pigments

The ideal pigment for solar-selective paint coatings would be high in solar absorptance, transparent in the infrared, have a low refractive index, be thermally stable, weather resistant, inexpensive, use no strategic materials, be readily available, and easily processed into a paint coating. On the previous program, pigment materials from Ferro, Harshaw, and Dupont were evaluated. The primary pigment selected was Ferro F-6331, and a backup pigment from Harshaw designated Meteor 7890. Various experimental pigment materials from both manufacturers were evaluated and provided clues to finding viable alternative pigments. Ferro IP-671A was prepared by sand milling, and showed slightly improved optical properties over conventional F-6331. The L-5062-2-1 pigment from Harshaw showed promising infrared transmittance, but lacked sufficient absorptance to be a serious candidate. Further attempts to improve this material by the vendor were somewhat successful. Test coatings of Harshaw L-5327-30 at 22-percent solids, 28 PVC in SR-125 binder showed α_s = 0.90 and ϵ_{TH} = 0.18. A 1-pound scaled-up replica sample designated L-5395-20 provided α_s = 0.87 and ϵ_{TH} = 0.18 at 30 PVC, 22-percent solids in SR-125 binder. Further scale-up to 10 pounds and designated L-5503-5 provided α_s = 0.86 and ϵ_{TH} = 0.12 at 28 PVC in 6247 and 20-percent solids.

Coatings based on the Harshaw "L" pigments and SR-125 gelled in approximately 3 days. A repeat test using the Cargill 6247 silicone-modified epoxy binder and L-5503-5 showed no gelling. The conclusion of the effort to establish a primary and back-up pigment for solar-selective paint coatings was considered only partially successful. While Ferro F-6331 remains the primary choice, the two pigments from Harshaw are backup candidates. The L-5503-5 contains no strategic materials and would thus be a slight favorite over the Meteor 7890, which contains chromium. The increased viscosity of coatings made with the L-5503-5 is considered an advantage over both the F-6331 and Meteor 7890 for gravure coating.

Binders

The types of binder material used in solar-selective paint coatings depends on the end use of the coating. Solar-paint coatings used in flat-plate collectors need to be made with binders having greater thermal stability than coatings used on passive thermal walls. The ideal binder material would be readily available, inexpensive, thermally stable to 450°F, compatible with solar-paint pigments, have a low index of refraction, resistant to ultraviolet (UV) degradation, and cure rapidly without elevated temperature.

Various binders were evaluated in prior programs. These included ethylene-propylene-diene (EPDM) and ethylene-propylene (EPM), which were used because their infrared transmittance facilitated a comparative evaluation of pigment materials. Aliphatic urethane was evaluated as a highly UV-resistant material with moderate thermal stability and room-ambient cure. Various silicones were evaluated because they offered the highest thermal stability of all organic binders, and were UV-resistant. The silicones required a long, high-temperature cure to achieve acceptable film properties.

Because the original intent of this effort was to develop a solar-selective paint coating for flat-plate collectors, the emphasis was on the thermal stability of the candidate binders. Thus, the binder emphasized throughout the various programs was General Electric SR-125, the most promising silicone evaluated. The need to use long, high-temperature cure cycles with this material was, however, a significant disadvantage.

Table 2. Optical Properties of 30 PVC Coatings with the Primary and Back-up Pigments

Choice	Pigment		Binder		Optical Properties	
	Trade Designation	Chemical Composition	Trade Designation	Chemical Composition	α_s	ϵ_{TH}
Primary	F-6331[a]	$FeMnCuO_x$	SR-125	Silicone	0.91	0.10
Backup	Meteor 7890[b]	$CuCrO_x$	DC-808	Silicone	0.88	0.16
Backup	L-5503-5[c]	$CuFeMnO_x$ epoxy	6247	Silicone-epoxy	0.86	0.12

[a] F-6331: Ferro Corp.
[b] Meteor 7890: Harshaw Inc.
[c] L-5327-30: Harshaw Inc.

A new investigation was initiated to find a binder that could cure under room ambient conditions. Such a binder would meet the requirements of the TISP coating, as well as the TSSP coating. The investigation involved attempts to catalyze silicone resins to reduce cure time and temperature, as well as a search for other types of binders. Various silicone binders were subjectively compared for degree of cure with and without catalyst. Table 3 shows the results of this effort.

Table 3 shows that there is no advantage gained by using the catalyst. Indeed, a disadvantage is in the reduced pot life. The catalyzed SR-125 gelled in 3 hours. These data showed that the heat-cured SR-125 remained the best candidate for the TSSP coating. Another approach to curing this material quickly was also investigated.

A silicon-controlled rectifier (SCR) infrared oven recently developed was found to be capable of curing solar paint coatings using the SR-125 binder at a rate of 200 ft/min. Unfortunately, none of the coating application subcontractors had this equipment, and, therefore, its use was limited to demonstrating feasibility.

Efforts continued to find a binder that cured at room ambient temperatures for the TISP coating. Various manufacturers were contacted and binder candidates selected. Table 4 shows the results of this effort. From these data, Cargill 6247 silicone-modified epoxy was selected for further investigation and development.

The two binders under investigation were the silicone-epoxy (6247) and the silicone (SR-125). Both binders showed resistance to elevated temperature exposure. Obviously, the silicone-epoxy would not be as resistant to long-term exposure, to elevated temperatures, or to UV radiation as the silicone. The silicone-epoxy, how-

Table 3. Solvent Resistance of Silicone Binders

Solvent	Binder, Catalyst, Cure Schedule					
	SR-125 No Catalyst	SR-125 Catalyzed with SRC-18			SR-141 Catalyzed with SRC-18	
	1 Hr @ 500°F	5 Min @ 250°F	2 Days @ RT	4 Days @ RT	10 Min @ 500°F	6 Days @ RT
Acetone	Good	None	None	Fair	Fair	Fair
Methyl alcohol	Not tested	None	None	None	None	Good
Toluene	Not tested	None	None	Poor	Fair	Fair
Methylene chloride	Not tested	None	None	Fair	Fair	Fair

Table 4. Candidate Binders for Solar Paint Coatings

Manufacturer	Material Recommended for Testing	Results	Comments
Cargill	6247 silicone epoxy	Good	Good all-around properties
	6260 silicone alkyd	Good	Poor solvent resistance
	2218 melamine	Poor	Poor temperature resistance
Dow Corning	DC-808 with catalyst	Good	Short pot life (3-5 hr)
	DC-804	Good	Requires heat curing (1 hr @ 450°F)
General Electric	SR-125 silicone	Good	Requires heat curing (1 hr @ 500°F)
	SR-141 silicone	Good	Requires heat curing (1 hr @ 400°F) and organometallic driers

ver, resists abrasion better than the silicone, and is thus less susceptible to film damage during handling and installation on a FPC. It also cures at room ambient temperatures, and thus has that advantage over the silicones.

The emittance of solar coatings based on the silicone-epoxy and silicone binders changed very little as a result of 500 hours of accelerated weathering exposure. Table 5 shows these data. Note that small differences in emittance were evident. The solar paint containing the silicone-epoxy binder showed a 2-percent drop in emittance. This was believed to be due to the stripping of layers of binder from the coating, thus reducing its optical cross-section. This resulted in greater transparency in the infrared and a lower emittance. It is well known that unmodified epoxy coatings have poor resistance to UV exposure. The increase in emittance of the solar paint containing the silicone correlates well with other long-term, accelerated weathering exposure data. Contamination of the surface by water spotting in the weatherometer may explain the increased emittance of coatings containing SR-125 silicone. The 6247 silicone-epoxy was further investigated as the binder of choice for the backup.

Table 5. Effect of Weatherometer Exposure on the Optical Properties of TSSP Applied by the Gravure Coating Process on Aluminum Foil

Exposure Time (hours)	30 PVC F-6331/SR-125		30 PVC F-6331/Cargill-6247	
	α_s	ϵ_{TH}	α_s	ϵ_{TH}
0	0.90	0.24	0.89	0.34
262	0.92	0.29	0.92	0.33
514	0.91	0.30	0.92	0.32

SOLAR ABSORPTANCE ENHANCEMENT COATING

Honeywell investigated the feasibility of using a low-index, transparent organic material as an antireflecting coating to reduce the surface reflectance of the selective black coating and to improve its absorptance. Successful enhancement could make the selective paint optically identical to selective black chrome.

A 30 PVC F-6331/SR-125 coating was applied to aluminum panels, cured, and the optical properties measured. The panels were then topcoated with FEP Teflon (DuPont FEP-120), the coating fused, and measurements again made. The results are listed in Table 6. From Table 6 it was observed that both solar aborptance and thermal emittance increased 3 to 4 percent. The improvement in absorptance due to the overcoating was considered very significant for solar-selective coatings. From Figure 1 it can be seen that a 3- to 4-percent improvement in solar absorptance from

Table 6. Optical Properties of 30 PVC F-6331/SR-125 Paint Coating Before and After Top Coating with FEP-120

Panel Code	Before Overcoat		After Overcoat	
	α_s	ϵ_{TH}	α_s	ϵ_{TH}
09787-20-9-13	0.88	0.15	0.91	0.19
09787-20-12-10	0.87	0.12	0.91	0.15
09787-20-13-10	0.88	0.14	0.91	0.18

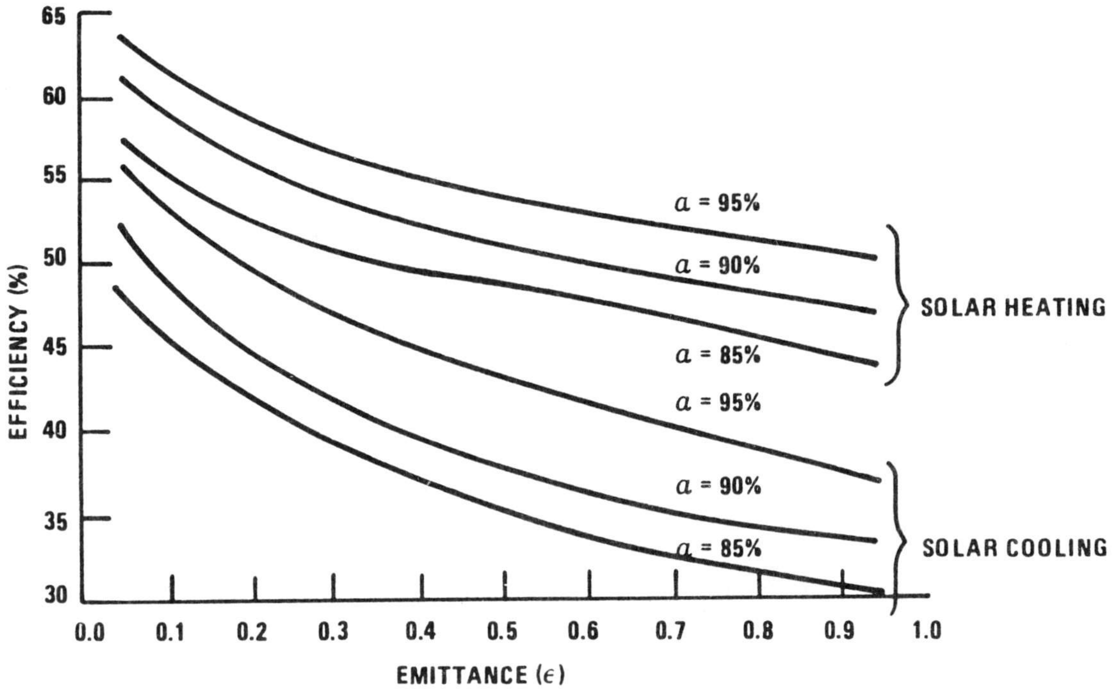


Figure 1. Collector Efficiency versus Coating Properties for Solar Heating and Cooling

$\alpha_s = 0.90$ to $\alpha_s = 0.94$, with an increase in thermal emittance from $\epsilon_{TH} = 0.15$ to 0.19, increases collector efficiency by 3 to 4 percent. The use of solar absorptance enhancement coatings could improve the optical properties of solar-selective paint coatings to be directly comparable to selective black chrome coatings at a fraction of the cost. The disadvantages to the system are the need for additional steps in applying the antireflectance (AR) coating, a means of raising the surface temperatures to the fusion temperature required for the FEP-120 coating, and maintaining the coating solution's consistency during procesing.

Experience with the FEP Teflon coating solution had indicated that additional effort was needed to effectively make use of it for this application. Since the use of AR coatings was essentially outside the scope of this program, further development of the coating was delayed until program goals could be satisfied. Unfortunately, meeting these goals required all subsequent program funds and, thus, the concept was not further investigated.

SOLAR TAPE MATERIAL INVESTIGATION AND DEVELOPMENT

The theory or concept of thickness-sensitive, selective paint coatings for solar energy was discussed previously. An interesting application of this concept in paint coating technology is the so-called solar tape. Conceptually, the solar tape has a selective paint coating on one side of a low-emitting substrate, and a pressure-sensitive adhesive (PSA) on the other (Figure 2). A release liner is used in contact with the PSA to prevent the tape from sticking to itself and the other area of the tape. A film of plastic may be applied over the paint surface to protect it from damage during its application to the FPC substrate. By peeling away the release liner from the PSA, the solar tape is made ready to apply to the FPC. The various material components comprising the solar tape are the protective film, solar paint coating, metal foil, adhesive, and release liner.

Solar Paint Coating

Two solar paint coatings were used throughout the development of the solar tape. Both made use of the Ferro F-6331 pigment and either the General Electric SR-125 silicone binder or the Cargill 6247 silicone-modified epoxy. The PVC of the coatings varied little, with 28-30 PVC being normal. Coating solids were varied significantly, primarily in an effort to control viscosity at the point of application. Each coating, whether it was the silicone or silicone-epoxy, had its good and bad points. The method of applying the coating for the solar tape was always by gravure. This is discussed in the later subsection: "Coating Application Investigation and Development."

Aluminum Foil

Prior work with the roll coating process required the use of aluminum foil. At that time, a 0.001-inch (1 mil)-thick 1100-0 aluminum foil was used. The quality of foil

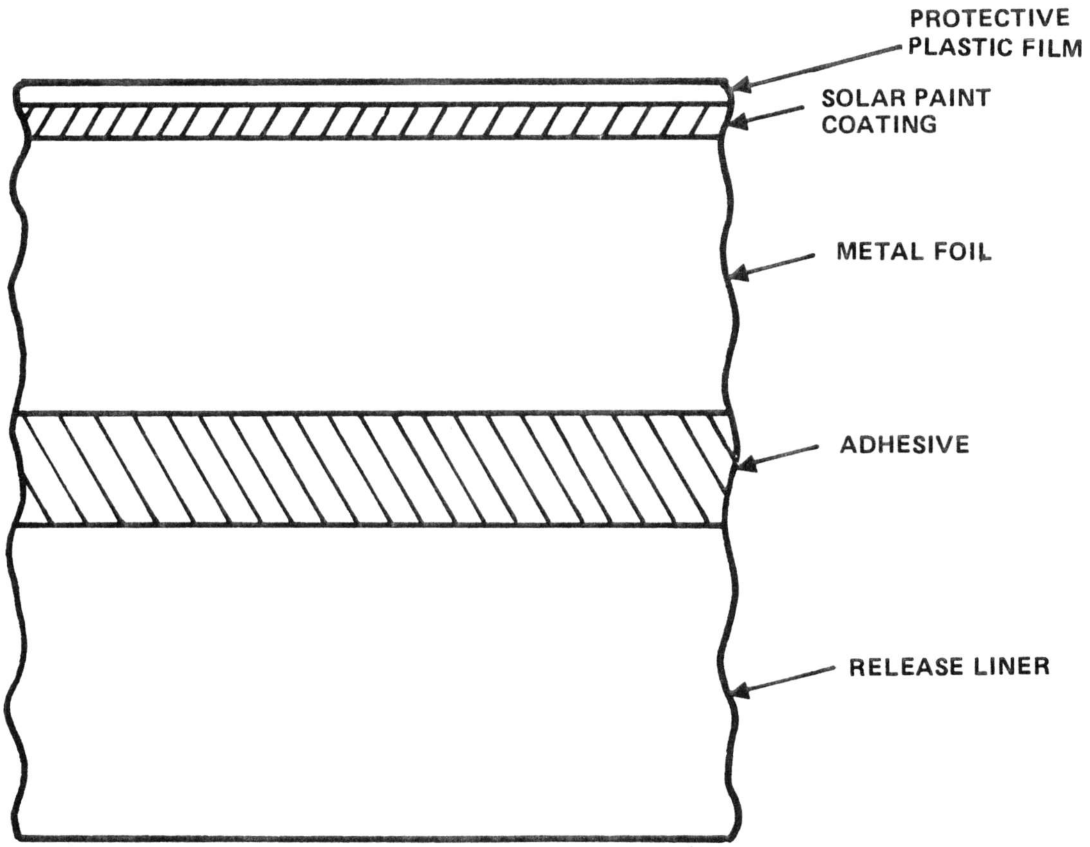


Figure 2. Diagram of Solar Tape Cross Section

was less than it should have been, resulting in a wrinkling during roll coating. It was also necessary to remove oils from the surface before use to improve coating adhesion. The foil needed must be able to withstand normal handling without either tearing or wrinkling, easily processed on normal production coating equipment, resistant to 700°F oven temperatures, and free of rolling oils and other lubricants that adversely affect paint adhesion.

During this effort, additional work was done to select a higher quality foil. Experience had shown that a 1-mil-thick 1100-0 aluminum foil tended to ripple when the release liner was removed. The appearance of the rippled foil was objectionable. Also, the foil was functionally questionable, since it could not be rollered flat against the FPC base, and there was concern for heat transfer through the foil to the collector base.

Aluminum foil 1-, 2-, and 3-mils thick was obtained from the Reynolds Metals Company, and adhesive and release liner applied to one side. Peeling away the release liner from each of these test samples showed that the wrinkling of aluminum foil was minimized with the 2- and 3-mil foil. Further investigation at Reynolds was used to select the right type of aluminum foil for solar-coating applications. The foil selected was their 2-mil No. 8079, which is 1183-T0.

Adhesive

The concept of a solar-selective tape for application to FPCs assumes that the material would be bonded to the substrate with a suitable adhesive. Adhesive thickness must be minimized to maximize heat transfer from the foil to the FPC base (presumably steel). The adhesive must be resistant to peeling, low offgassing, thermally stable to FPC conditions, and provide galvanic insulation between aluminum and steel to prevent corrosion.

Prior work demonstrated the feasibility of using a 2-mil-thick adhesive between aluminum and steel to prevent galvanic corrosion. After 864 hours of exposure to accelerated weathering, no corrosion could be found on either the steel or aluminum surfaces exposed.

Further investigation of adhesive type, thickness, offgassing, thermal properties, and edge effects, as well as further environmental testing, was needed to verify commercial and residential applicability of the concept. To accomplish this, a number of adhesive manufacturers were contacted. Various adhesives were selected for evaluation. Adhesives were evaluated by determining peel strength, thermal resistance, cost, and release paper compatibility. The results of this evaluation are listed in Table 7.

Table 7. Adhesive Candidates for the Solar-Selective Tape Concept

Manufacturer	Material Recommended for Testing	Comments
Dow Corning	DC 280A silicone	Good when used with catalyst. Continues to wet-out release liner on aging, resulting in excessive strength.
	DC 281 silicone	Requires a 5-minute, 300°F cure for high-temperature stability. Continues to wet-out release liner on aging, resulting in excessive strength.
3M	Scotchgrip 4914 acrylic	Good peel strength to 500°F.
	Scotchgrip 4910 acrylic	Charred at 400°F.
	Scotchgrip 4268 acrylic	Outgasses at 300°F.
H.B. Fuller	SC-1393	Good temperature resistance; high cost.
	SC-2307	High cost; blisters above 350°F.
Dennison	Densil 1078	High cost; available as a transfer film only.

From the data in Table 7, two adhesives were selected for final evaluation: DC 280A silicone; and 3M Scotchgrip 4914 acrylic pressure-sensitive adhesives (PSA).

The temperature resistance of the silicone adhesive was approximately 500°F, compared to 400°F for the acrylic adhesive. The acrylic adhesive was easier to apply and handle than the silicone adhesive, and did not continue to wet-out the release liner upon standing, as did the silicone adhesive. The subcontractors were familiar with acrylic adhesive systems and somewhat hesitant to work with the silicone adhesives. Both materials had acceptable adhesion, outgassing and corrosive effects on steel and aluminum substrates. At temperatures of 400°F, the acrylic adhesive discolored slightly. The bond between the substrate and foil was not broken. The absorber surface could be easily repaired by applying fresh solar-selective tape over the old surface.

Release Liner

It is necessary to protect the PSA on the solar tape with a film (release liner) that is easily removed prior to application of the tape. Adhesion between the film and the solar tape must hold the liner in place, but not so that its removal wrinkles or otherwise distorts the foil. The investigation of release liner materials was carried on concurrently with the investigation of adhesives. While the adhesive candidates were under investigation, manufacturers of release liners were contacted. A list of those contacted and their response may be found in Table 8.

Table 8. Release Liner Manufacturers Contacted

Manufacturer	Material Candidates	Results of Lab Investigation
Akrosil	No recommendations for silicones	
Boise Cascade	No recommendation	
Daubert Chemical	No recommendations for silicones	
H.P. Smith	Polysilk	
	Solventless systems	
	8514	Silicone wet-out, poor release.
	8714	Acceptable 3-month storage.
	8503	Acceptable, but difficult to handle.
International Paper	No recommendations for silicones	
Plover Paper	No recommendations for silicones	

It was apparent from the response of the manufacturers contacted that releasing from silicone PSAs was a significant problem. Apparently, the contact area between the liner after initial application to the PSA increases upon storage. As the area of contact increases, the adhesion increases until the liner is difficult to remove and the substrate distorts. Indeed, evaluation of the releasing characteristics of the liners verified this.

Dow Corning DC 280A pressure-sensitive adhesive was applied to aluminum foil by spraying from a solvent solution. Solutions of adhesive with and without a benzoylperoxide catalyst were used. Adhesive thickness was also varied. Liner materials were applied to the adhesive-coated foil and rolled flat. The initial release was evaluated, as well as the release after various storage times. The results of the evaluation showed that none of the release liner materials released well from DC 280A silicone PSA after storage. H.P. Smith No. 8714 release liner was acceptable after 3 months of storage, but failed with continuing storage. The No. 8503 liner material was found acceptable, but difficult to handle. In view of the difficulties with release liners not releasing well from silicon PSAs it was decided that high-temperature acrylic PSAs would be investigated.

Protective Film

The concept of the solar foil requires it to be used on other substrates, specifically, FPCs. Application of the foil to the FPC base requires the removal of the release liner, positioning of the solar tape on the substrate, adhering the tape, smoothing the bubbles, and rollering the surface. All of these operations can damage the black solar-selective paint. Although the paint is somewhat resistant to abrasion, it was believed that a protective plastic film over the paint would assure its good appearance.

A film of 0.001-inch-thick polyester film (Mylar, Type A) was used for this purpose. It was applied to the painted surface at the time of applying the release liner by roll laminating equipment. The protective film adheres to the paint substrate by electrostatic charge and is easily removed after the tape has been applied to the FPC base. The protective film is especially useful for coatings based on the SR-125 silicone applied by the gravure coating process. These coatings tend to be more susceptible to damage by abrasion than those based on Cargill 6247 applied by the same process.

The cost of the solar tape materials is summarized in Table 9. The cost per square foot for high-volume production runs would be approximately $0.15/ft^2, and $0.22/ft^2 for low-volume production.

COATING PROCESSING INVESTIGATION AND DEVELOPMENT

Previous work with the paint solutions uncovered a problem with long-term container stability. Certain paint solutions were unstable within 2 weeks after for-

Table 9. Cost Estimate for Materials and Processing of Solar Tape at Low and Medium Volume

Component	Cost, $/Square Foot	
	Low-Volume[a] Material Application	Medium-Volume[b] Material Application
Protective film	0.020	0.014
Paint coating	0.011	0.005
Aluminum foil	0.063	0.052
Adhesive	0.033	0.023
Release liner	0.023	0.016
Total:		
— Material	0.127	0.110
— Processing	0.096	0.039
— Material and processing	0.223	0.149

[a] 10,000 ft2
[b] 1 million ft2

mulation, while other paints were stable for up to 2 years. Optical properties were significantly degraded with the storage of some paint solutions. Particle size, particle wetting, paint viscosity, and paint solids content all contributed to the problem of pigment settling and solution stability.

Paint Solution Stability

Initial work was done with solution agitation in the reverse roll coater application during the previous program. This method improved solution uniformity and did not adversely affect the coating thickness control. To avoid the need for coating agitation, other methods of preventing the pigment from falling out of the paint upon standing were investigated.

Paint coatings based on F-6331 pigment and SR-125 binder were ball-milled to pigment particle size ranges of 2-4μm, 9-11μm and 19-21μm. No other ingredients such as anti-caking or wetting agents were used. Coatings were blended with solvents to produce 10-, 15-, 20- and 25-percent solids coatings. The coatings were then stored for up to 17 months, with periodic samples evaluated for changes in optical properties. All but the 8-hour samples for top and bottom were thoroughly agitated prior to dip application of the coating. Coatings were then applied to aluminum substrates, cured, and optical properties measured. These data may be found in Tables 10 and 11.

TABLE 10. The Effect of Storage Time on the Optical Properties of 10- to 25-Percent Solids, 30 PVC F-6331/SR-125 Solar Paint Coating With 2-4μm Pigment Size

Solution Settling Time	Solids (%)							
	25		20		15		10	
	α_s	ϵ_{TH}	α_s	ϵ_{TH}	α_s	ϵ_{TH}	α_s	ϵ_{TH}
Initial	88	33	89	14	80	5	81	4
8 hours, top half	88	24	86	9	82	4	76	4
8 hours, bottom half	88	36	86	15	86	6	81	3
8 hours, combined	88	29	87	12	83	5	79	3
1 week	88	33	86	14	85	5	79	3
2 weeks	88	35	88	17	86	6	78	4
1 month	88	37	87	18	86	6	80	4
2 months	88	38	88	20	86	8	79	3
4 months	89	41	89	20	87	8	75	4
7 months	88	51	87	39	83	9	65	4
17 months	91	76	88	49	89	38	76	4

TABLE 11. The Effect of Storage Time on the Optical Properties of 20-Percent Solids, 30 PVC F-6331/SR-125 Solar Paint Coating With Pigment Particle Size Ranges of 2-4 μm, 9-11 μm, and 19-21 μm.

Solution Settling Time	Particle Size (μm)					
	2-4		9-11		19-21	
	α_s	ϵ_{TH}	α_s	ϵ_{TH}	α_s	ϵ_{TH}
Initial	89	14	90	16	92	20
8 hours, top half	86	9	72	5	78	5
8 hours, bottom half	86	15	92	22	92	26
8 hours, combined	87	12	91	15	88	17
1 week	86	14	92	22	92	21
2 weeks	88	17	91	17	93	23
1 month	87	18	93	18	93	20
2 months	88	20	92	19	92	18
4 months	89	20	-	-	-	-
7 months	87	39	94	34	93	33
17 months	88	49	-	-	-	-

Table 10 shows that the only solution stable for 17 months is the 10-percent solids as evidenced by the consistency of optical properties. The 15-percent-solids coating showed stability for 7 months, and the 20- and 25-percent solids coatings for 4 months. Since no wetting agents were used in the coatings to reduce the tendency for pigment agglomeration, the pigment was free to agglomerate upon settling. The tendency of the coatings to change in optical properties is more pronounced in coatings at higher solids than lower solids. This may be due to the increased proximity of pigment particles within the paint coating at higher solids.

Table 11 shows that the stability, as evidenced by optical property changes, is also related to pigment particle size. However, the effect appears to be less significant than that for the effect of solids. Another interesting aspect of the data in Table 11 is the higher absorptance of coatings with a larger particle size (19-21μm) rather than for those with a smaller (2-4μm) particle size. Apparently, the larger particle size provides a better surface for solar absorptance. Unfortunately, the emittance of coatings with the larger pigment particles tends to be higher than with smaller pigment particles.

Better wetting of the pigment by the binder may improve the coating's shelf stability. Wetting agents and anti-caking agents may improve the shelf stability of the coating.

Paint Milling Procedures

Still another approach to improving pigment wetting, therefore reducing agglomeration while maintaining optical properties, was to explore other milling processes. Of particular interest was sand milling, since it appears to be the coming industry standard. The process is efficient, requiring but a few hours of milling to accomplish what ball milling required days to do. It also promises control of pigment particle size as well as improved pigment wetting. The comparison of ball milling and sand milling equipment may be seen in the diagrams in Figures 3 and 4, respectively.

Because a relationship between milling and the optical performance of the coating had been established, it was necessary to study the methods of pigment milling which are standard in the paint industry. The method used for small batches would not lend itself to large batches of paint due to the need to keep the pigment particle's size well below that of normal paint coatings while minimizing mill sluff contamination. A grind of 2-4μm by ball milling required approximately 4 days. This was accompanied by considerable wear and sluffing of the grinding media with contamination of the paint. While the effect of contamination did not appear to detract from the optical properties of the paint, the time required and method used to produce the paint was of concern.

A literature review as well as contacts with local manufacturers was used to locate appropriate sand milling equipment. Other methods of milling were also explored,

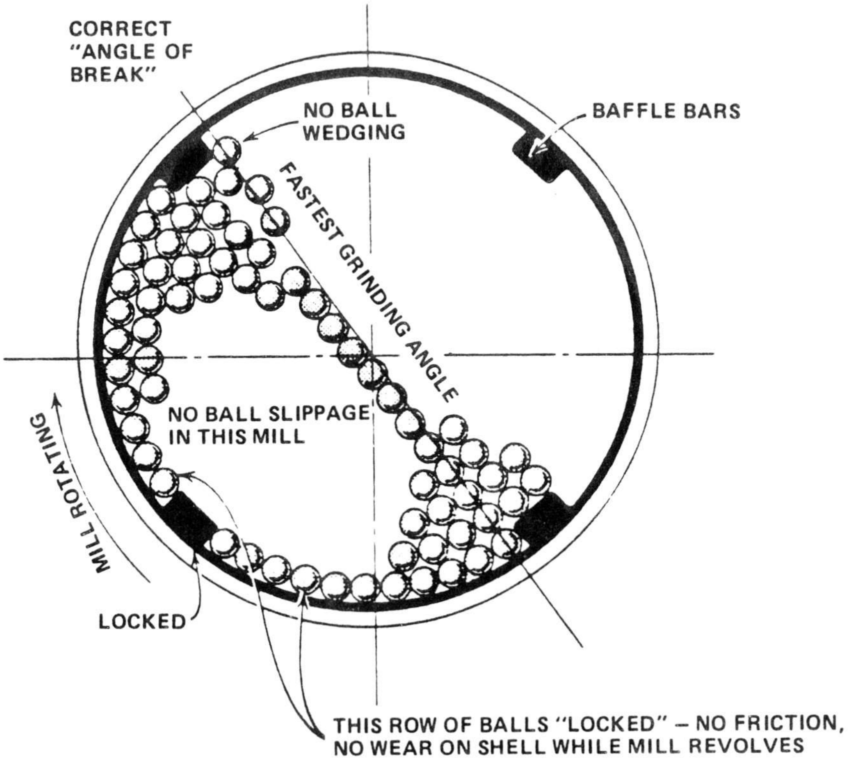


Figure 3. Diagram of a Ball Mill

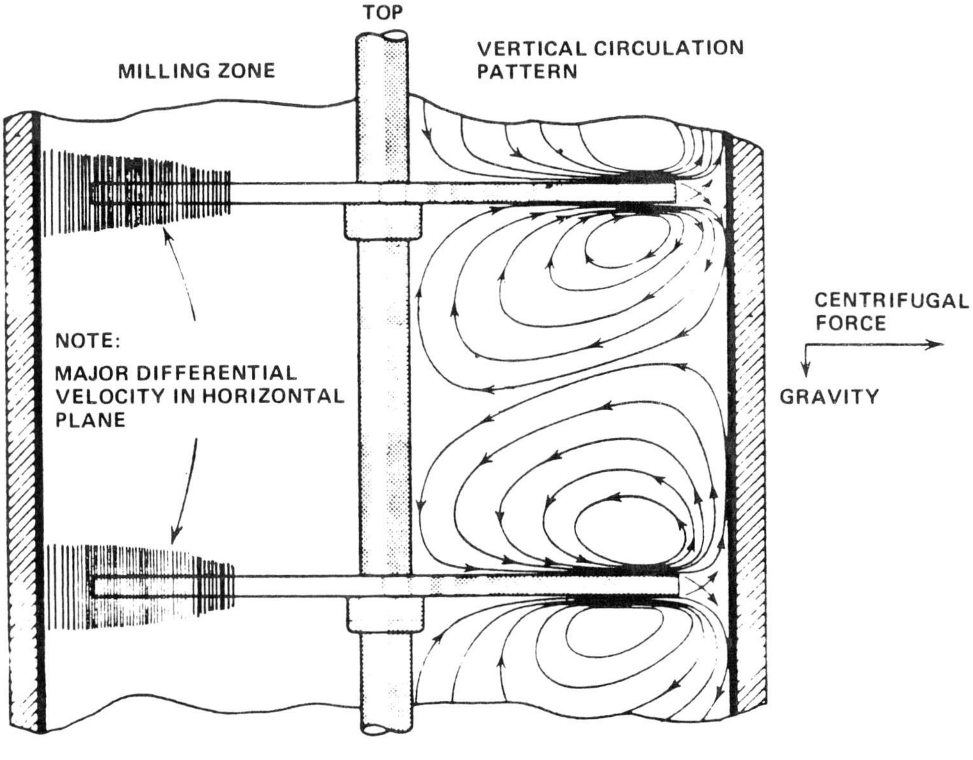


Figure 4. Diagram of a Sand Mill

but failed to show as much promise as sand milling. A local manufacturer then produced 1 gallon of 50-percent solids 30 PVC F-6331/SR-125 solar coating for evaluation.

Observations of the process revealed excessive viscosity of the coating, as evidenced by the globs of paint coming out of the mill and the amount of time required to get the paint through the mill. A draw down of the paint showed that the pigment had been milled to a smaller particle size range than was achieved with ball milling. The optical properties of the coating were equivalent to the same coating prepared by ball milling. The solution stability of the sand-milled coating was greater than that of the ball-milled coating.

Laboratory experimentation with a Cowles Disolver (Figure 5) was also done. The results of the experiment were not promising. The equipment could not break down particle agglomerates to produce a range of 2-4μm. Thus, this type of equipment was not pursued. The conclusion of the work with ball milling, sand milling and the disolver was that the sand mill processing of solar paint coatings produces coatings with equivalent or better properties than either of the other two methods explored. Thus, sand milling was selected as the process for large-scale solar paint manufacturing.

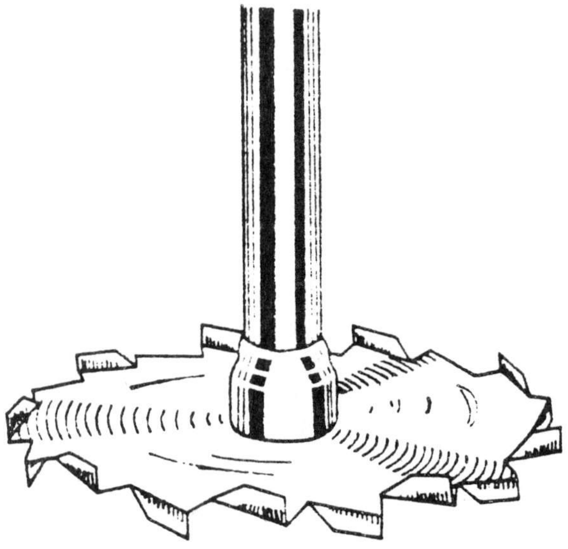


Figure 5. The Impeller of the Cowles Dissolver

COATING APPLICATION INVESTIGATION AND DEVELOPMENT

Various paint application procedures were evaluated throughout the last two programs. The purpose of the evaluation was to determine which procedures would provide the best optical properties, and also to identify procedures, and their limitations, that are commonly used. The paint application procedures investigated were dip coating, spray coating, roll coating and gravure coating.

Dip Coating

Dip coating was used exclusively throughout this, and prior solar paint programs to establish the comparative properties of experimental solar paint coatings. The process lends itself to a high degree of repeatability through control of the substrate withdrawal rate from the coating, as well as the paint coating PVC and solids content. The degree of control obtainable with the dip coating process may be best understood by noting the data in Table 12.

Table 12 shows that the emittance of replica solar paint coatings is essentially the same. For instance, replica samples (ID 73 and ID 74) show $\epsilon_{TH} = 0.06$. Numerous other data in Table 12 can be used for comparison. It is evident, however, that, at dip coating withdrawal rates of 1 and 5 inches per minute, repeatability between samples is less than at withdrawal rates of 2 to 4 inches per minute. It was observed that, at the lower rate, there was a time lag in the dip coater cross-head movement that caused a jerking motion in the sample which evidenced itself in an irregular paint film. This apparently accounted for some variability in the emittance values for samples dip coated at 1 inch per minute.

At the higher dip coat withdrawal rate of 5 inches per minute, any irregularity in the withdrawal rate is magnified in slight thickness changes and noticeable variation in coating emittance. This particular dip coating machine provided highly repeatable coating applications when used between 2 and 4 inches per minute.

Dip coat application of solar-selective paint coatings has been solidly demonstrated in a laboratory environment. There is reason to believe that the dip process could be a viable production process, since parameters for control are relatively easily managed. A high-quality dip coating machine would be needed that withdrew substrates uniformly and evenly without jerking motions. Hydraulic systems would suffice nicely for this type of application but other systems may be equally well suited with proper design and engineering. The application of solar-selective paints by dip coating does not limit the substrate to flat panels. However, in the interest of efficiency, masking of the nonfunctional side may be accomplished by placing them back-to-back in masking frames. Dip coating limits the throughput to a small- to medium-size production facility. The paint would need to be agitated in the tank and adequate tank ventilation provided to protect workers. The cost of filling the tank with paint, cleaning the panels prior to coating, and equipment needed to cure the paint would all need to be considered in the total plan. A schematic of the dip coating production line is shown in Figure 6.

Table 12. Optical Properties of 30 PVC F-6331/SR-125 Paint Coatings Applied by Dip Coating

Dip Rate (in/min)	Coating Solids (% by wt), Identification (ID), Solar Absorptance (α_s) and Total Emittance (ϵ_{TH})																										
	30%			29%			28%			27%			26%			25%			24%			23%			22%		
	ID	α_s	ϵ_{TH}	ID	α_s	ϵ_{TH}	ID	α_s	ϵ_{TH}	ID	α_s	ϵ_{TH}	ID	α_s	ϵ_{TH}	ID	α_s	ϵ_{TH}	ID	α_s	ϵ_{TH}	ID	α_s	ϵ_{TH}	ID	α_s	ϵ_{TH}
1	1	0.91	0.16	11	0.91	0.12	21	0.91	0.11	31	0.90	0.10	41	0.91	0.10	51	0.90	0.06	61	0.89	0.06	71	0.89	0.05	81	0.88	0.05
	2	0.91	0.12	12	0.91	0.10	22	0.91	0.09	32	0.90	0.08	42	0.90	0.08	52	0.90	0.06	62	0.89	0.05	72	0.88	0.05	82	0.88	0.04
2	3	0.91	0.17	13	0.91	0.14	23	0.91	0.11	33	0.90	0.10	43	0.90	0.09	53	0.90	0.06	63	0.89	0.06	73	0.89	0.06	83	0.89	0.06
	4	0.92	0.16	14	0.91	0.16	24	0.91	0.12	34	0.90	0.10	44	0.91	0.10	54	0.90	0.06	64	0.89	0.06	74	0.89	0.06	84	0.89	0.06
3	5	0.92	0.22	15	0.91	0.19	25	0.91	0.14	35	0.90	0.13	45	0.91	0.12	55	0.90	0.07	65	0.90	0.08	75	0.90	0.08	85	0.90	0.08
	6	0.92	0.21	16	0.91	0.19	26	0.91	0.15	36	0.90	0.12	46	0.91	0.11	56	0.90	0.07	66	0.90	0.08	76	0.90	0.07	86	0.90	0.07
4	7	0.92	0.28	17	0.92	0.24	27	0.91	0.19	37	0.91	0.17	47	0.91	0.14	57	0.91	0.10	67	0.91	0.10	77	0.90	0.07	87	0.90	0.07
	8	0.92	0.28	18	0.91	0.25	28	0.91	0.18	38	0.91	0.17	48	0.91	0.13	58	0.91	0.10	68	0.90	0.09	78	0.90	0.09	88	0.90	0.07
5	9	0.92	0.33	19	0.92	0.33	29	0.91	0.24	39	0.91	0.22	49	0.91	0.17	59	0.91	0.13	69	0.91	0.12	79	0.90	0.10	89	0.90	0.09
	10	0.92	0.35	20	0.92	0.32	30	0.91	0.27	40	0.91	0.24	50	0.91	0.18	60	0.91	0.15	70	0.91	0.14	80	0.91	0.12	90	0.91	0.10

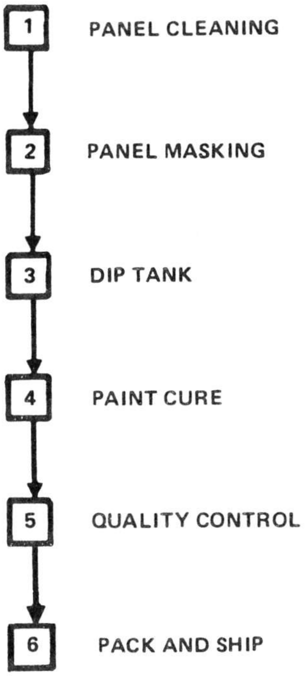


Figure 6. Schematic of Solar-Selective Paint Coating Application by Dip Coating

Spray Coating

A number of spray coating procedures were used to apply solar-selective paint coatings. Conventional suction feed and pressure feed spray guns were used, as well as electrostatic spray equipment. Virtually all of these types of equipment are widely used throughout the industry for applying paint coatings.

Suction-Feed Spray Coating

The first attempt to use spray coating equipment was to apply experimental solar-selective paint coatings to aluminum discs for measurement of optical properties. This was done with a Paasche Air Brush and #3 and #5 fluid tip combinations. The lack of repeatable data showed the use of manual application techniques to be undesirable under these conditions. Once solar-selective paint coatings were developed, however, other attempts to spray apply them met with more success, as will be discussed later.

A DeVilbiss TGA-501 suction feed spray gun with a #92 air cap and #402-E needle was used to apply 30 PVC F-6331/SR-125 coatings at 25-, 12.5-, and 6.25-percent solids and 20- to 25-lb/in^2 line pressure to aluminum substrates. The spray was applied with greater than normal care to control gun-to-substrate distance in an effort to simulate automatic or semiautomatic equipment. The data from this series of experiments are shown in Table 13.

Table 13 shows that the solar paint can be made selective by conventional suction-spray coating techniques with somewhat less selectivity than that for the dip coating process. Optical property changes resulting from an abrasion resistance test showed typical changes in absorptance of −2 and in emittance of +2. Thus, the abrasion resistance of these coatings was found to be equivalent to those applied by dip coating.

Table 13. Optical Properties of 30 PVC F-6331/SR-125 Paint Coating Applied by Suction Feed Spray

Relative Spray Gun Traverse Speed	Coating Solids (%)					
	25		12.5		6.25	
	α_s	ϵ_{TH}	α_s	ϵ_{TH}	α_s	ϵ_{TH}
Fast	0.92	0.34	0.91	0.26	0.88	0.07
Medium (normal)	0.92	0.44	0.92	0.21	0.92	0.13
	0.92	0.47	0.92	0.24	0.92	0.14
Slow	0.92	0.60	0.93	0.32	0.91	0.17

NOTE: DeVilbiss TGA-501 spray gun with # 92 air cap and 402-E needle, 25-lb/in^2 line pressure.

The feasibility of using the spray coat approach for solar-selective paint coatings was demonstrated with conventional suction feed equipment. Either semiautomatic or automatic spray coating equipment would be required to maintain gun-to-part distance and traverse speed. Paint agitation during the process is recommended to maintain the uniformity of the paint and to prevent the settling that tends to occur at low solids. The spray coating process, using either semiautomatic or automatic equipment, should provide a moderately selective product. The process lends itself to small-, medium- or perhaps even high-volume production. It has the advantage of coating only one side of a substrate, although overspray on the back side does occur. It could be used for either panels or foil (with the suitable handling equipment). The main disadvantage of the spray coating process is in current requirements to control solvent emissions. The main solvent used in the coating is either xylene or toluene, either of which would require ventilation and perhaps recovery. It is possible that with sufficient paint volume, the manufacturers for the resin could be persuaded to reformulate their materials to meet current solution standards of various locals. A schematic of a spray coating production line is shown in Figure 7.

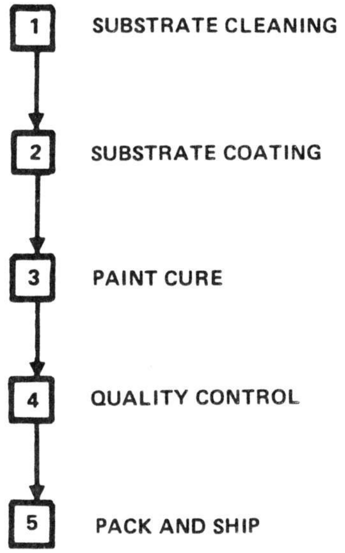


Figure 7. Schematic of Solar-Selective Paint Coating Application by Spray Coating

Electrostatic-Pressure Feed Spray Coating

The feasibility of using electrostatic spray coating equipment was investigated. Graco 60 KV electrostatic pressure feed spray equipment was used to evaluate its potential for use with solar paint coatings.

A 30 PVC F-6331/SR-125 paint was diluted to 15-percent solids for spraying. The equipment could spray with pressure feed, either with or without electrostatic charge. Several test panels were coated with and without the electrostatic charge. All passes of the spray gun were at medium (normal) speed. Results of the experiment may be seen in Table 14.

Table 14 shows that optical selectivity was achieved by using electrostatic-pressure spray equipment. Typical absorptance/emittance values of $\alpha_s = 0.90/\epsilon_{TH} = 0.32$ were achieved with or without electrostatic charge for gun passes at a medium speed. These data compared with the data in Table 13 for the siphon feed spray of a 12.5-percent coating indicate no advantage in using either electrostatic-pressure or pressure-only spray equipment as far as the optical properties are concerned. However, the use of electrostatic spray does conserve paint and, therefore, offers an economic advantage over nonelectrostatic spray coating systems. These savings can be substantial for medium- to high-volume production. It was believed that further reduction of coating solids would have produced optical properties equivalent to those obtained with suction feed equipment, but funding and time limitations prevented this from being explored.

Table 14. Optical Properties of 30 PVC F-6331/SR-125, 15-Percent Solids Paint Coating Applied by Electrostatic-Pressure Feed Spray

Relative Spray Gun Traversing Speed	Test Sample Number	Electrostatic and Pressure		Test Sample Number	Pressure Only	
		α_s	ϵ_{TH}		α_s	ϵ_{TH}
Medium	1	0.89	0.33	5	0.90	0.31
Medium	2	0.90	0.32	6	0.91	0.34
Slow	3	0.96	0.50	-	-	-
Slow	4	0.94	0.46	-	-	-

Note: Graco 60 KV electrostatic pressure feed.

The feasibility of using electrostatic-pressure spray equipment to apply solar-selective paint coatings was demonstrated. Either semiautomatic or automatic spray coating equipment should be used to maintain the gun-to-part distance and traversing speed. Paint should be agitated during the process to maintain paint uniformity and prevent the settling that tends to occur in low solids, unmodified paints. This type of equipment should provide a moderately selective product. The process would lend itself to any size of production operation but perhaps, because of equipment costs, may be more suited to medium- or high-volume production. Electrostatic spray coating conserves more paint than is possible through either suction or pressure-feed spraying techniques. However, there is the disadvantage of overspray wrap-around that both uses more paint and may require removal prior to curing the paint. These advantages and disadvantages should be carefully considered and evaluated prior to establishing a production facility. The schematic for an electrostatic-pressure spray coating production line is shown in Figure 8.

Roll Coating

Roll-coating equipment was used to demonstrate the first high-speed application of solar-selective paint coatings. Figure 9 shows a diagram of a reverse roll coater. Solar paint coatings had already been successfully applied by both the dip and spray coating procedures. Both dip and spray coating application procedures have limitations for high-speed processing. A Revaplast Laminator, made by the Bruderhaus Co. (Germany), was used to apply solar paint to aluminum foil by a reverse roll coating process. Although a number of problems arose in accomplishing the task, all of them had to do with unfamiliarity with the equipment, poor foil quality, paint settling, and ventilation. The feasibility of using reverse roll coating equipment for applying solar paint coatings was demonstrated. Table 15 shows the results of the third and final trial of the process.

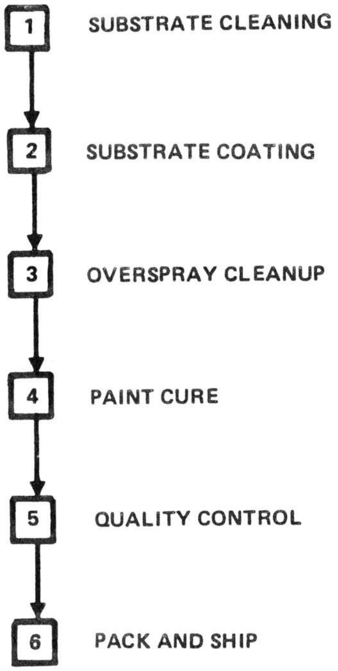


Figure 8. Schematic of Solar-Selective Paint Coating Application by Electrostatic Pressure Spray Coating

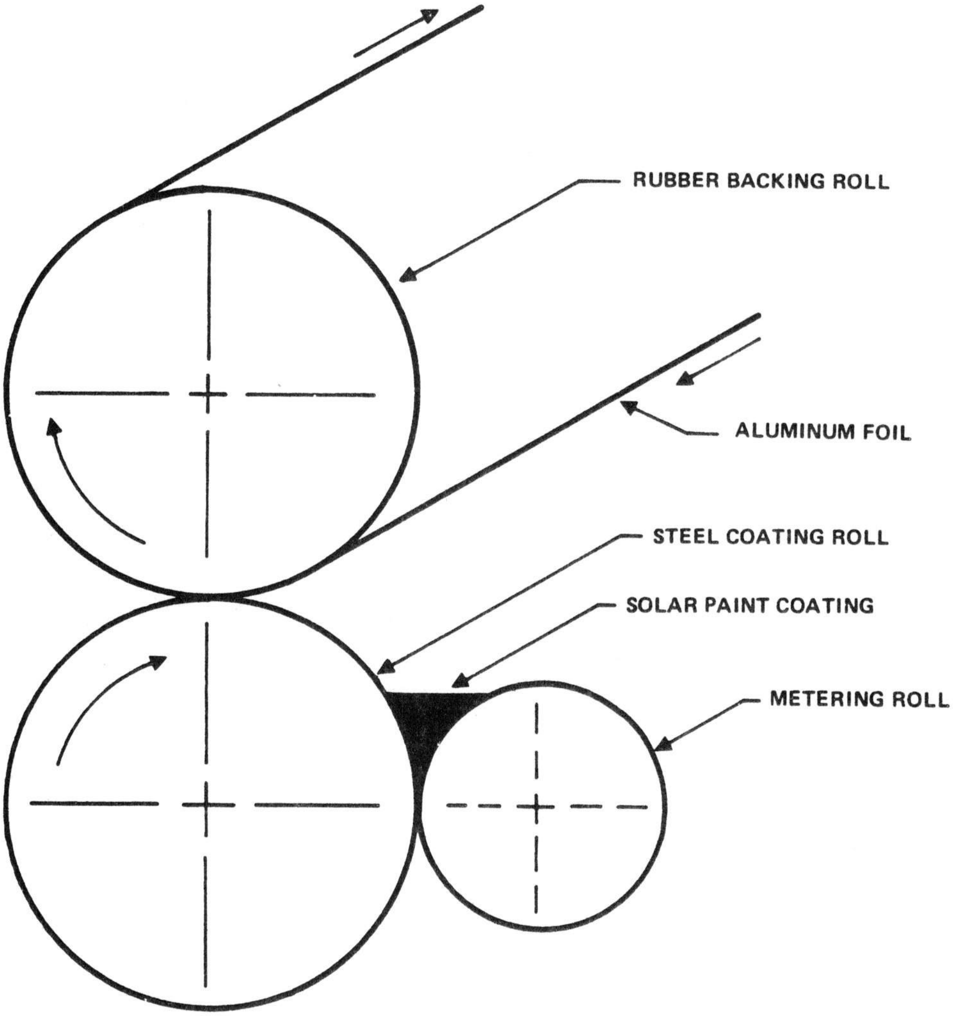


Figure 9. Diagram of Reverse Roll Coater Applying Solar Paint to Aluminum Foil

Table 15. Optical Properties from Second Scale-Up Production of 30 PVC F-6331/SR-125 Solar Paint on Aluminum Foil

Coating[a] Rate (ft/min)	Coating Solids (% by wt), Identification (ID), Solar Absorptance (α_s) and Emittance (ϵ_{TH})																	
	25.0			18.8			14.3			13.9			10.7			8.4		
	ID	α_s	ϵ_{TH}	ID	α_s	ϵ_{TH}	ID	α_s	ϵ_{TH}	ID	α_s	ϵ_{TH}	ID	α_s	ϵ_{TH}	ID	α_s	ϵ_{TH}
18	32	0.92	0.40	4	0.90	0.35	8	0.88	0.26	28	0.89	0.17	16	0.89	0.14	23	0.86	0.09
21	-	-	-	-	-	-	-	-	-	29	0.88	0.14	-	-	-	-	-	-
25	34	0.92	0.37	-	-	-	-	-	-	-	-	-	20	0.88	0.18	25	0.87	0.12

[a] **Revaplast Laminator,** Bruderhaus Co., Germany.

Table 15 shows that good optical properties were achieved at various paint-coating-solids concentrations and equipment coating line speeds. Subsequent improvements in paint solution stability, agitation of paint, and higher-quality aluminum foil would improve the final product. Higher line speeds may be possible as techniques are further enhanced.

Reversed roll coating applications of solar-selective paint is considered a process for small to medium manufacturing facilities. Limited line speeds restrict its use in high-volume production. Figure 10 shows a schematic of a roll coating process for applying solar-selective paint coatings. A unique advantage of this equipment over gravure coating equipment is that it can be used to apply not only the solar paint, but also the adhesive and release liner. Adhesive thicknesses needed for the solar tape exceed the capabilities of gravure equipment. On the other hand, roll coating equipment is not as well suited for coating thickness control as is gravure coating equipment.

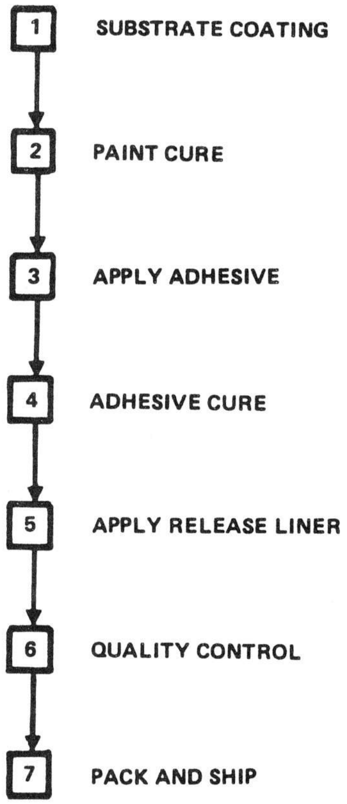


Figure 10. Schematic of Solar Selective Paint Coating, Adhesive and Release Liner Application by Roll Coating

Gravure Coating

The process of gravure coating has been used for high-speed application of inks and various coating materials to thin films of plastic and metals. It is similar in concept to reverse roll coating, but with two distinct differences, as shown in Figure 11. The

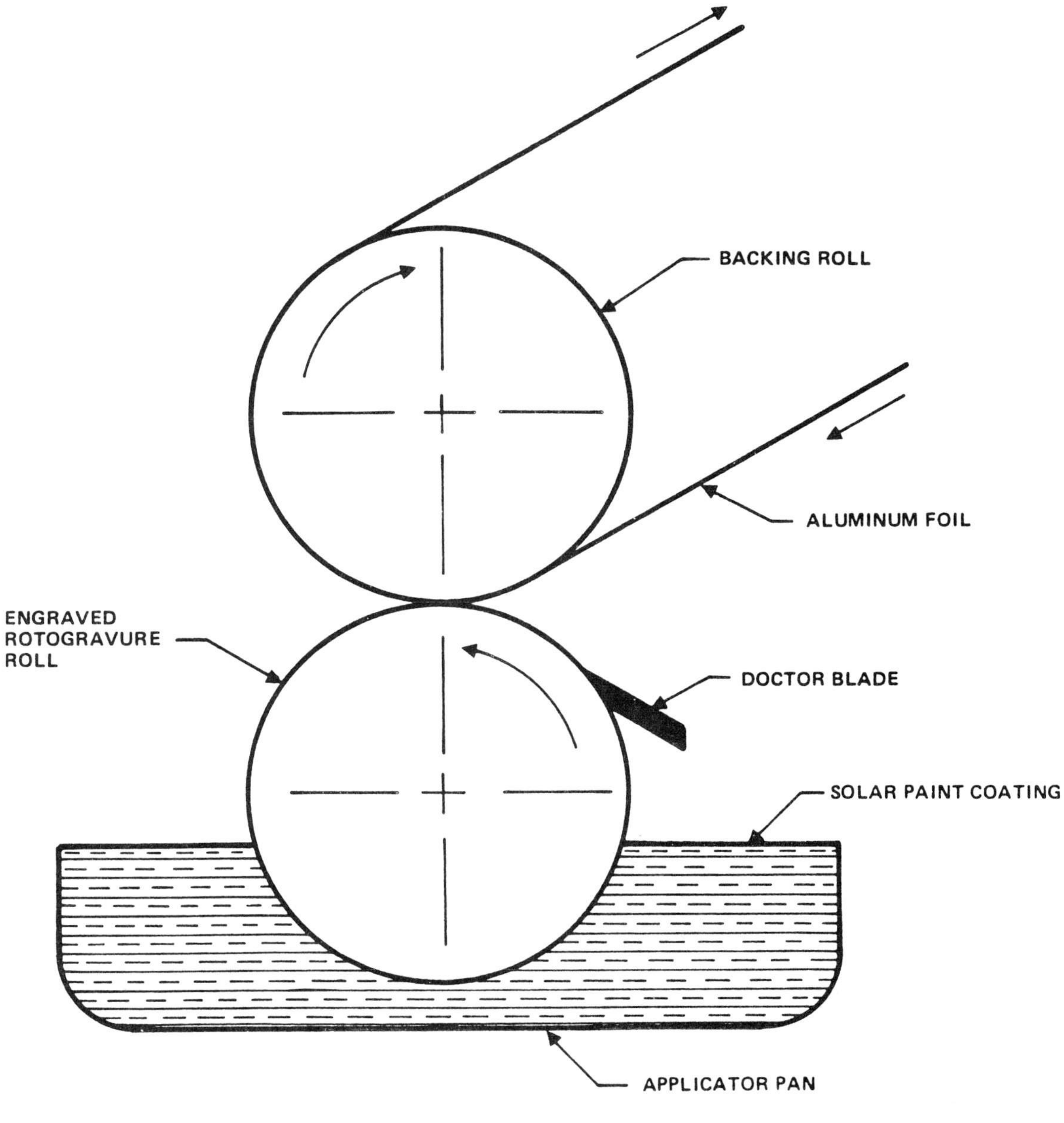


Figure 11. Diagram of Gravure Coater Applying Solar Paint to Aluminum Foil

coating roll is etched with a pattern that is designed to deliver precise quantities of coating to the contacting film. Also, a doctor blade in close proximity to the coating roll removes any excess coating from the roll. The equipment generally is capable of very high web (line) speeds, while maintaining a precise film thickness control of the coating.Extremely thin coating films can be applied, thus providing a method for applying thickness-sensitive selective paint coatings. Of all previously attempted processes, this process appeared to hold the greatest promise for high-volume solar coating applications. A significant effort to demonstrate the feasibility of using gravure coating was followed by successively larger runs to demonstrate production feasibility.

Batches of solar paint, using both ball milling and sand milling procedures, were prepared and evaluated. Solar paints that were sand-milled showed a higher viscosity than those that were ball-milled with the equivalent particle size, solids, PVC and binder. It was learned that higher viscosity is beneficial for the application of solar paints than lower viscosity at the equivalent solids. This aids in applying thinner films with the gravure coating process, which results in a lower emittance and, hence, greater selectivity. In all, three separate runs were made. Each time, valuable information about the equipment and the coatings was obtained. Table 16 summarizes these data.

Table 16 shows that, with each successive run, the optical properties of solar paints applied by the gravure coating process continued to improve. Using sand milling procedures to prepare the paint coatings were beneficial both in reducing milling time and in increasing coating viscosity. This was probably due to both an improved pigment wetting, as well as a narrower particle size distribution than is possible with ball milling.

The abrasion resistance of the silicone coatings based on SR-125 was improved somewhat by reducing the PVC from 30 to 28, but remains a concern. Care in handling foil coated with this system is recommended. It may be possible to reach a balance between good abrasion resistance and good optical properties by further adjusting PVC. Further effort with this system was not pursued due to time and funding limitations.

The abrasion resistance of the silicone-modified epoxy coatings, based on the 6247 resin, remained excellent throughout the gravure-coating effort. Initial concern about the optical properties was dismissed upon successful completion of the final run. Further effort with this system may enhance optical properties even further without significantly compromising the abrasion resistance.

Table 16. Optical and Abrasion Resistance Properties of Various Solar Paint Coatings Applied to Aluminum Foil by Gravure Coating

Run No.	Coating Description Pigment/Binder	Milling Technique	Solids Applied (%)	Web Speed (ft/min)	Quantity Coated (lineal ft)	Optical Properties		Abrasion Resistance
						α_s	ϵ_{TH}	
1	30 PVC F-6331/SR-125	Ball-milled	30	100	450	0.91	0.25	Poor
	30 PVC F-6331/SR-125	Ball-milled	50	100	450	0.92	0.20	Good
	30 PVC F-6331/6247	Ball-milled	50	200	300	0.90	0.30	Excellent
2	30 PVC F-6331/SR-125	Sand-milled	25	150	1500	0.90	0.12	-
	30 PVC F-6331/6247	Ball-milled	40	200	200	0.92	0.26	-
	30 PVC F-6331/6247	Ball-milled	30	200	750	0.92	0.26	-
3	28 PVC F-6331/SR-125	Sand-milled	40	180	5000	0.90	0.07	Fair
	28 PVC F-6331/6247	Sand-milled	40	200	5000	0.90	0.15	Excellent

The feasibility of using the gravure coating process with solar coatings, based on either SR-125 silicone or 6247 silicone-modified epoxy, was demonstrated. Both types of coatings offer advantages and disadvantages. Coatings based on the SR-125 silicone have significant advantages in temperature resistance, better optical properties, and UV resistance over those based on the 6247 silicone-modified epoxy. On the other hand, coating based on the 6247 silicone-modified epoxy have significant advantages in abrasion resistance and appearance over those based on the SR-125 silicone. Further work with both systems may be needed to suit a particular production condition.

Applying TSSP coatings by the gravure coating process was demonstrated to be feasible from a production standpoint. High-quality solar coatings were produced throughout all of the runs. Applying a coating to 10,000 ft^2 of aluminum foil, with the resulting properties discussed, clearly showed gravure coating to be a medium- to high-volume process. The cost of the equipment is high compared with that needed for either dip or spray coating. However, regulations for solvent emission may significantly increase the real cost of spray coating. A schematic of a gravure-coating production line is shown in Figure 12.

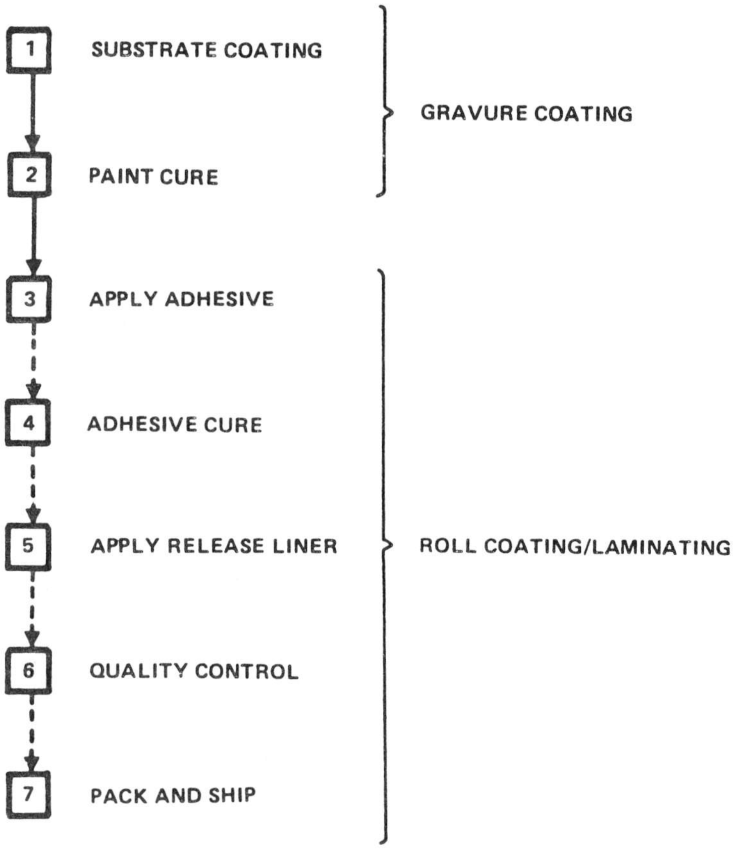


Figure 12. Schematic of Solar Selective Paint Coating Application by Gravure Coating and Adhesive and Release Liner Application by Roll Coating

Figure 12 must be interpreted in the light of the additional processing needed for a usable product. Use of the foil as a solar tape requires the application of both pressure-sensitive adhesive and release liner. Experience to date indicates that this is best accomplished with roll laminating because the adhesive thickness needed for solar tape exceeds that which can be applied by gravure coating equipment. Thus, several additional steps would follow the cure of the coating, as shown by the dotted portion of the schematic in Figure 12.

Summary

Each of the processes for applying solar-selective paint coatings has advantages and disadvantages when compared with the other. Production situations should be a major consideration in selecting the method of application. These include equipment available, new equipment needed, and shop practices. The market for a high-performance, low-cost, solar-selective coating produced by the individual manufacturer needs to be established. A brief summary of process information gained to date may be found in Table 17.

Table 17. Comparison of Various Equipment and Processes for Applying Solar-Selective Paint Coatings to Either Panels or Foil

Process	Optical Properties		Critical Parameters	Advantages/ Disadvantages
	α_S	ϵ_{TH}		
Dip coating	0.90	0.06	• Coating solids • PVC • Withdrawal rate • Coating agitation	• Precise thickness control • Low equipment cost • High-quality product • Large quantity paint needed • Special dip coater required • Frequent dip tank monitoring • Paint must be agitated • Limited to panels
Spray coating				
Suction Feed	0.92	0.13	• Gun-to-part distance • Gun traverse speed • Coating solids (vary) • PVC • Coating agitation	• Tend to get high absorptance • Semi- or automatic equipment required • Solvent and paint emissions • Paint must be agitated • Limited to panels
Pressure feed	0.91	0.34	• Gun-to-part distance • Gun traverse speed • Coating solids (vary) • PVC • Pot pressure • Coating agitation	• Tend to get high absorptance • Semi- or automatic equipment required • Solvent and paint emissions • Paint must be agitated • Limited to panels
Electrostatic pressure feed	0.90	0.32	• Gun-to-part distance • Gun traverse speed • Coating solids (vary) • PVC • Pot pressure • Coating agitation	• Tend to get high absorptance • Semi- or automatic equipment required • Solvent and paint overspray cleanup • Solvent and paint emissions • Paint must be agitated • Limited to panels
Roll coating	0.88	0.14	• Coating solids • PVC • Web speed • Coating agitation	• Medium production speed • Emission control with minimal venting • High equipment cost • Slow web speed • Paint must be agitated • Limited to foil
Gravure Coating	0.90	0.07	• Coating milling • Coating solids • PVC	• Medium-to-high production speed • Emission control with minimal venting • Precise thickness control • High-quality product • High equipment cost • Paint should be agitated • Limited to foil

Section 3
Thickness-Insensitive Selective Paint (TISP) Development

Coatings described thus far must be thickness-controlled to provide show-through of a high-reflecting substrate to achieve a low emittance. The need to precisely control thickness limits the versatility and acceptability of these coatings to use on FPCs. Other passive solar applications could make use of selective paint coatings if there were no need to control the film thickness during the application. Capture ratios (α_s / ϵ_{TH}) for such coatings can be as low as 3:1 or even 2:1 if absorptance is sufficiently high.

It is beneficial to reduce or eliminate the need for thickness-control of the solar paint coatings. This gives the paint coatings greater versatility for commercial and residential applications. It was demonstrated that incorporating highly reflective metallic particles, such as aluminum flake, in the existing solar paint would accomplish this.

In theory, the thickness of the black coating is controlled within the paint coating rather than through the process of applying the paint coating. Since the paint coating contains the low-emitting substrate, its selectivity is independent of the type of surface to be painted.

CONVENTIONAL APPROACH

A more-or-less conventional approach previously pursued was to use aluminum flakes as the low-emitting substrate in the solar paint coating. The major problem in the development of so-called TISP coatings has been the inability to replicate the optical properties of the original coatings. The feasibility of this concept was demonstrated when test coatings showed a capture ratio (α_s/ϵ_{TH}) of 3:1 with $\alpha_s = 0.89$ and $\epsilon_{TH} = 0.31$. The reasons for this nonreproducibility were largely unknown. All ingredients of the coating were suspect, but the primary concern focused on the aluminum flake pigment, since its behavior in test coatings appeared to be unpredictable.

The goal of the current effort was to continue the development and optimization of TISP coatings to achieve a capture ratio of 6:1 with $\alpha_s = 0.90$ and $\epsilon_{TH} = 0.15$ and establish criteria for controlling the behavior of the metallic pigment. Within this framework, durability, solution stability and batch-to-batch repeatability were to be established. The specific goals are listed in Table 18.

Table 18. Specific Objectives for Thickness-Insensitive Selective Paint

Objective	Plan
Optical	
α_s	≥ 0.90
ϵ_{TH}	≤ 0.15
Durability	
Mechanical	
Adhesion	Pass tape test
Abrasion resistance	Pass cheesecloth test
Environmental	
Accelerated weathering	Pass 20-year simulated exposure
Cycling humidity	Pass 10-day MIL-STD-810 exposure
Test site exposure	9 months
Reproducibility	
Solution stability	No appreciable settling in 8 hours
Appliclation technique	
$\Delta\ \alpha_s$	0.03
$\Delta\ \epsilon_{TH}$	0.05
Scale-up	
Honeywell	
Substrate coating	32 ft^2
Paint solution	20 gallons
Test site	80 ft^2
Cost (¢/ft^2)	
Material	1
Application	
Home owner	1
Commercial	6

Background

The conventional approach or concept for initially developing TISP coatings made use of the 30 PVC F-6331/SR-125 paint coatings previously developed for TSSP coatings. Other binders were tried in an attempt to achieve a system that would cure under room ambient conditions. Urethane and acrylic base coatings were compared with those using SR-125 binder (Table 19). Neither the urethane nor the acrylic coatings performed as well optically as did the silicone-based paints.

Solution-stability experiments with coatings left standing for up to 72 hours after mixing showed dramatically improved solar absorptance. Changes in solar absorptance from $\alpha_s = 0.64$ initially to 0.89 after 72 hours of aging were evident (Table 20). Emittance values changed little during this time. One explanation for the change in optical properties was that the aluminum flakes underwent a surface change during this time that aided the orientation of the particles into a more planar condition more closely approximating the optical properties of a plate. Specifically, it is not known how this happens.

Table 19. Optical Properties of Spray- and Brush-Applied 30 PVC F-6331 (Urethane,[a] Silicone,[b] and Acrylic[c] Coatings with Alcoa 2468 Aluminum Flake)

Aluminum Flake (% by wt)	Urethane				Silicone				Acrylic			
	Spray		Brush		Spray		Brush		Spray		Brush	
	α_s	ϵ_{TH}	α_s	ϵ_{TH}	α_s	ϵ_{TH}	α_s	ϵ_{TH}	α_s	ϵ_{TH}	α_s	ϵ_{TH}
10	0.87	0.52	0.83	0.47	0.93	0.57	0.91	0.57	0.93	0.69	0.93	0.73
15	0.79	0.35	0.81	0.44	0.92	0.57	0.91	0.55	0.93	0.64	0.93	0.72
20	0.81	0.36	0.81	0.41	0.92	0.44	0.90	0.45	0.93	0.61	0.93	0.70
25	0.78	0.31	0.80	0.42	0.91	0.39	0.90	0.48	0.93	0.58	0.93	0.66
30	0.76	0.31	0.80	0.44	0.90	0.31	0.90	0.48	0.92	0.55	0.92	0.63

[a] MIL-C-83286, Deft Chemical Co., Irvine, CA

[b] SR-125, General Electric Co., Waterford, NY

[c] MIL-L-81352, Enmar Co., Wichita, KA

Table 20. Effect of Solution Aging on the Optical Properties of Thickness-Insensitive 30 PVC F-6331/SR-125/2468 Coatings

Aluminum Flake[a] (%)	Relative Coating Thickness[b]	Time After Mixing, Absorptance, Emittance					
		0 Hours		24 Hours		72 Hours	
		α_s	ϵ_{TH}	α_s	ϵ_{TH}	α_s	ϵ_{TH}
10	Light	0.90	0.64	0.90	0.61	0.92	0.60
	Wet	0.90	0.66	0.91	0.68	0.92	0.68
20	Light	0.82	0.49	0.90	0.49	0.91	0.52
	Wet	0.78	0.49	0.91	0.58	0.92	0.66
30	Light	0.74	0.38	0.90	0.46	0.91	0.49
	Wet	0.56	0.34	0.90	0.52	0.91	0.57
40	Light	0.64	0.34	0.88	0.38	0.89	0.40
	Wet	0.58	0.32	0.89	0.40	0.90	0.54

[a] 2468, Aluminum Company of America, Pittsburgh, PA

[b] Spray-applied application, light = light coating, wet = wet coating

Also noted in Table 20 was the difference in optical properties resulting from the application of thin-versus-thick coatings. These data suggested the need to either control the application thickness of the coating, or to develop the coating further to reduce or eliminate this need. The first approach was not acceptable, since the intent of this type of coating was to be free from the need to control the thickness of the application.

Repeatability and durability were also evaluated in the previous work with the data summarized in Table 21. It was apparent from these, and previously mentioned data, that it was, indeed, possible to develop a TISP coating by incorporating reflective metal flakes in the TSSP coating. Improvements were needed in optical properties, solution stability, sensitivity-to-application techniques, and repeatability.

Table 21. Optical Properties of Spray-Applied, 30-Percent Solids, 30 PVC F-6331 Thickness-Insensitive Coatings Before and After 1750 Cycles of Abrasion Exposure

Binder Coating	Aluminum Type	Flake (%)	Before		After	
			α_s	ϵ_{TH}	α_s	ϵ_{TH}
SR-125	2468	15	0.92	0.59	0.87	0.59
		30	0.90	0.41	0.80	0.43
Acrylic	2468	15	0.93	0.64	0.91	0.64
		30	0.92	0.55	0.88	0.58
Urethane	2468	15	0.79	0.35	0.71	0.37
		30	0.76	0.31	0.69	0.33

Development

The continued development of TISP coatings was directed toward three major areas of materials and processing development: 1) improving the optical properties of the paint coating itself; 2) decreasing the sensitivity of optical properties to application techniques; and 3) identifying and developing suitable binders commensurate with these goals. To facilitate this effort, each component of the coating was investigated separately, developed, and optimized as much as possible. Combinations of these materials were then brought together in test coatings and formulations in various forms to optimize properties.

Metallic Pigments — Highly reflective metallic pigments are the key element in achieving the low emittance of a thickness-insensitive paint. Aluminum flakes and nickel powders were selected as candidate metal pigments because of their optical properties, durability, and costs. Aluminum flakes were emphasized.

Aluminum Pigments — Table 22 lists the candidate aluminum flakes which were selected on the basis of particle size, shape, and size distribution. Aluminum

Table 22. Particle Sizes of Various Aluminum Pigments

Aluminum Pigment[a]		Particle Size (μm)	
Type	Code	Range	Average
Powder			
Leafing	7100	5-20	20
	5100	10-30	25
	2100	10-50	50
Non-leafing	3100	10-30	30
	2000	10-50	45
Paste			
Leafing	769	-	10
	565	5-30	20
	462	10-50	40
Non-leafing	796	3-25	20
	588	3-50	25
	586	5-40	35

[a] Pigments from Aluminum Company of Canada.

flakes are more or less leaflike. While the powders are dry, pastes have organic solvents, usually mineral spirits. Particle sizes in Table 22 were estimated from the scanning electron micrographs (SEM) provided by the Aluminum Company of Canada (Alcan).

The evaluation of aluminum pigments was to determine their emittance when used in a paint coating. Paint coatings of 30-percent solids and 30 PVC were made by mixing aluminum flakes with SR-125 silicone in toluene. Samples were spray-coated, air-dried, and cured at 500°F for 1 hour. Their optical properties are shown in Table 23.

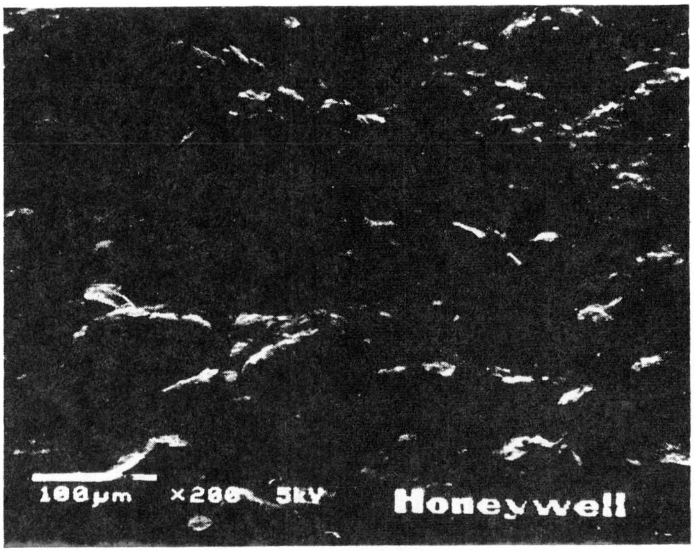
It can be seen from Table 23 that there are two distinctly different patterns in the coatings using aluminum flakes for a pigment. Coatings using leafing flakes, powders or pastes provide a lower emittance than those with smaller flakes. This essentially verifies the results of work on the previous program. The 462 leafing paste and the 2100 leafing powder show emittance values of 0.22 and 0.23, respectively, in silicone coatings.

A SEM examination of coatings containing aluminum pigments show two patterns which can be seen in Figures 13, 14, 15 and 16. In general, leafing pigments appear to interleave and lay flat in the coating, while non-leafing pigments do not. Small pigments tend to produce a more broken surface than larger ones in the coating. The emittance of coatings containing aluminum pigments tends to correlate both with the type (leafing or non-leafing) and size of the pigment. Large pigments tend to provide lower-emittance coatings than small pigments. Leafing pigments tend to

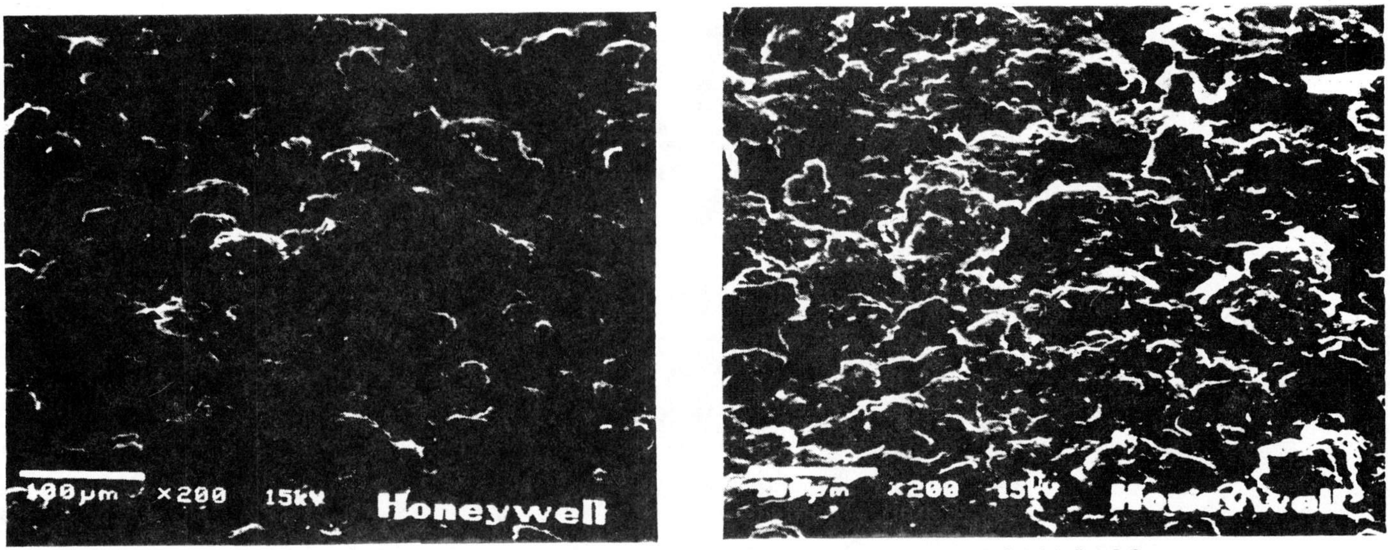
Table 23. Emittance of 30 PVC Aluminum-Pigmented/SR-125 Coatings

Aluminum Pigment[a]		Pigment Particle Size	
Type	Code	(μm) (avg)	ϵ_{TH}
Powder			
Leafing	7100	20	0.29
	5100	25	0.25
	2100	50	0.23
Non-leafing	3100	30	0.46
	2000	45	0.36
Paste			
Leafing	769	10	0.24
	565	20	0.24
	462	40	0.22
Non-leafing	796	20	0.35
	588	25	0.26
	586	35	0.28

[a] Pigments from Aluminum Company of Canada.



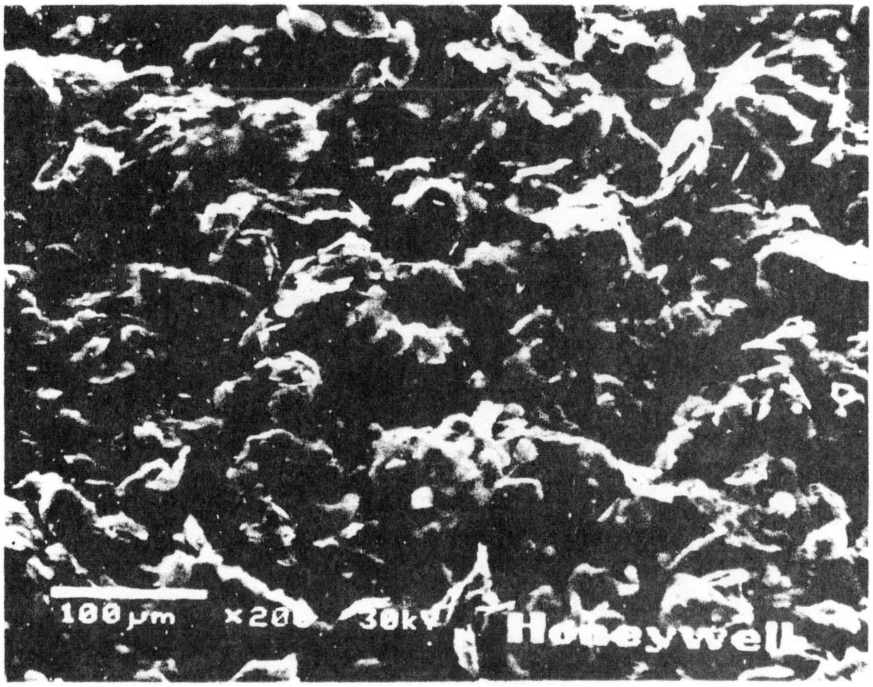
ALCAN 7100



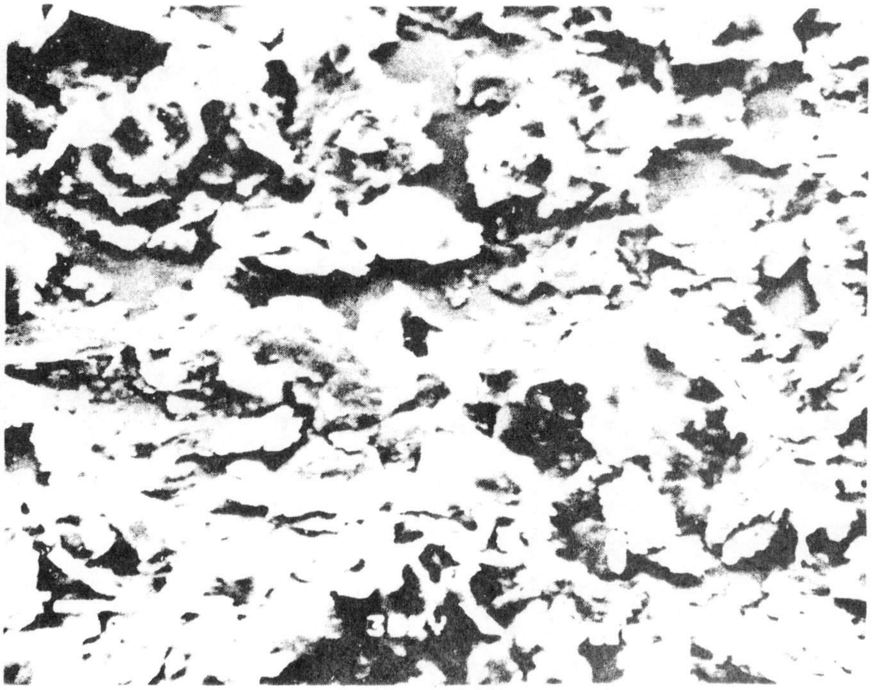
ALCAN 5100

ALCAN 2100

Figure 13. SEM of Leafing Aluminum Powders/SR-125 Coatings

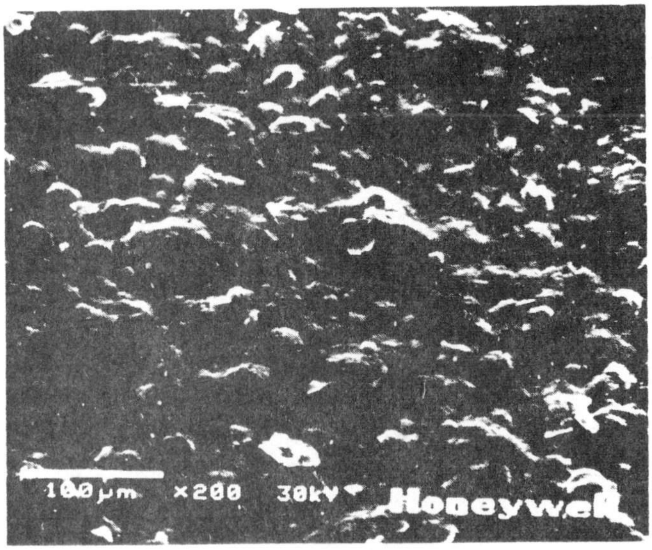


ALCAN 3100

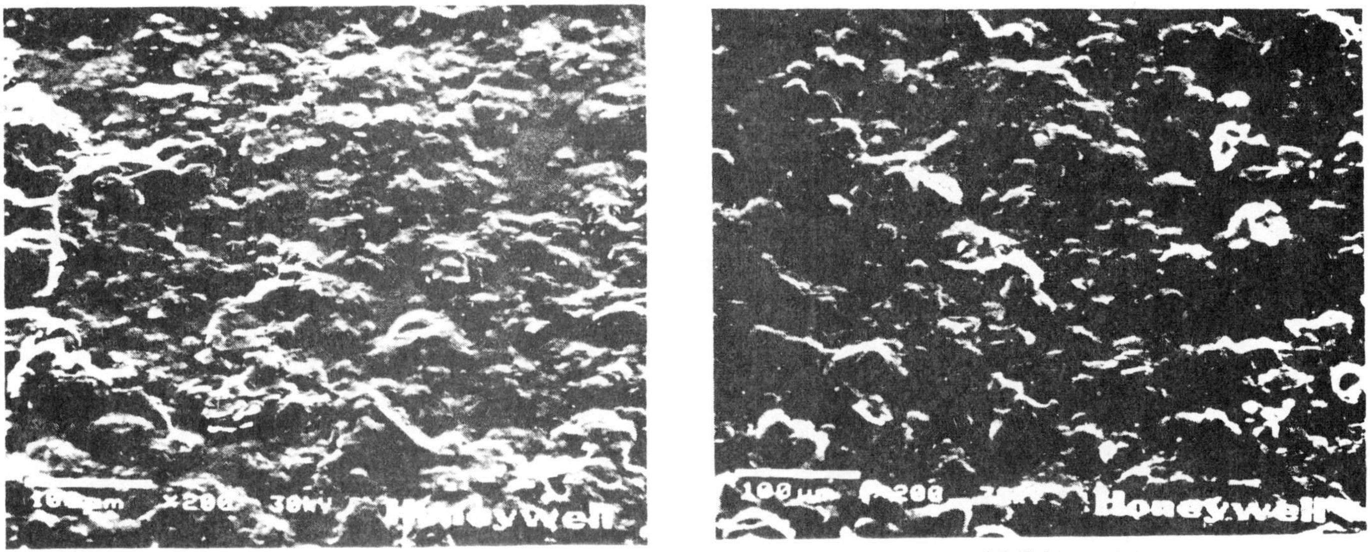


ALCAN 2000

Figure 14. SEM of Non-Leafing Aluminum Powders/SR-125 Coatings



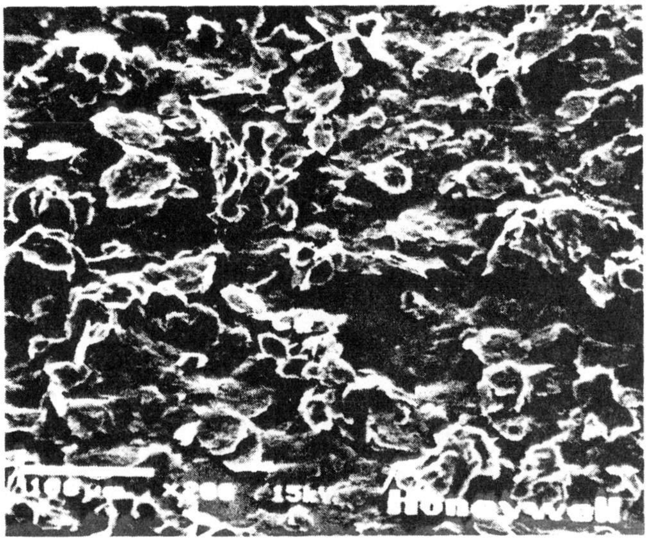
ALCAN 767



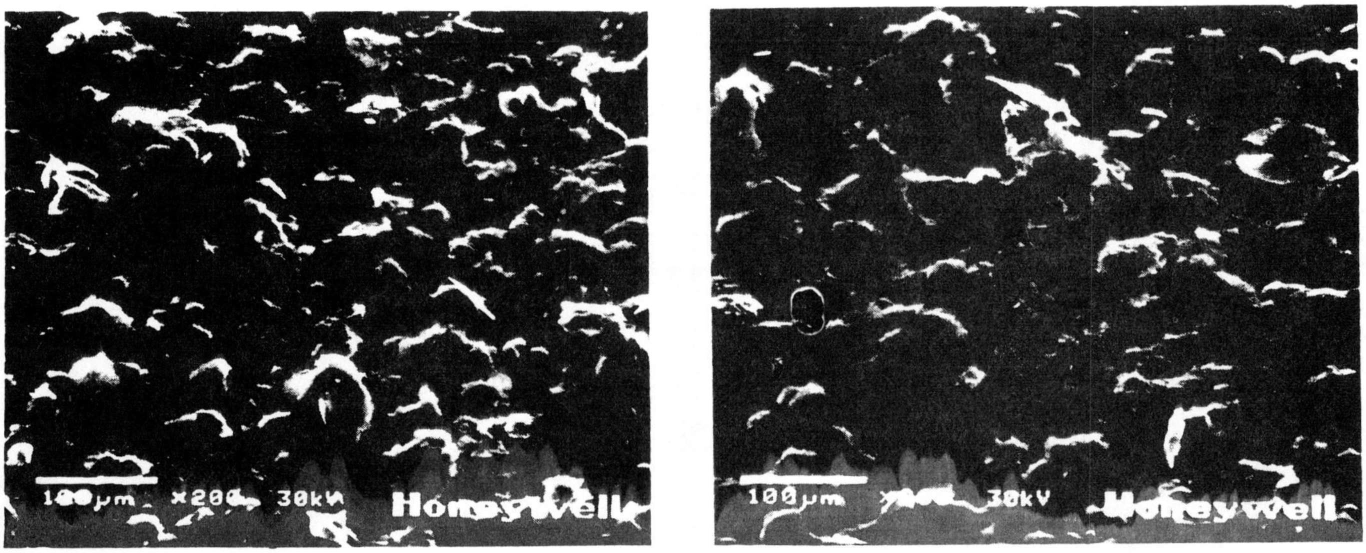
ALCAN 565

ALCAN 462

Figure 15. SEM of Leafing Aluminum Pastes/SR-125 Coatings



ALCAN 796



ALCAN 588

ALCAN 586

Figure 16. SEM of Non-Leafing Aluminum Pastes/SR-125 Coatings

provide lower-emittance coatings than non-leafing pigments of equivalent size. Apparently, the irregular surface from small and/or non-leafing pigments exposed to infrared radiation traps the radiation, resulting in a higher emittance. Conversely, large and/or leafing pigments, which provide smooth surfaces in coatings, tend to result in a lower emittance.

Nickel Pigments — Another type of metal pigment was found that holds promise for solar paint coatings: nickel powders from the International Nickel Co. (INCO). Unfortunately, the powders were available in relatively few particle sizes (Table 24). Type 123 nickel powder has a regular shape and spiky surface. Types 287 and 255 have a chain-like structure of fine, irregular particles. Type 756 nickel powder is milled from Type 123.

Table 24. Optical Properties of 30 PVC Nickel-Pigmented/SR-125 Coatings

Nickel Pigment Type	Pigment Particle Size (μm)[a]	α_s	ϵ_{TH}
287	2.6 to 3.3	0.92	0.75
255	2.2 to 3.0	0.92	0.76
123	3 to 7	0.88	0.71
756	-	-	0.40

[a] From INCO brochure.

Nickel powders were evaluated in a manner similar to that used for aluminum pigments. Nickel powders were mixed with SR-125 silicone and toluene to make a 30-percent solids, 30 PVC coating. Applied and cured coatings were evaluated for optical properties and the data recorded (Table 24). Types 287, 255 and 123 nickel powders exhibited a dark color and were found to have a high solar absorptance. However, none of the coatings made from any of the nickel powders showed low emittance. Thus, nickel powders were not investigated further.

Test Paint Coating Formulations — Alcan 769, 565 and 462 leafing aluminum pastes were selected for further evaluation. Quantities of 30-percent solids, 20 PVC F-6331/SR-125 silicone coating were combined with candidate aluminum pigments. The quantity of aluminum pigment varied from 10 to 30 percent by weight, based on coating and aluminum paste solids. The coatings were mixed and allowed to stand for 1-hour and 24-hour periods, spray applied to test substrates, cured, and measured for optical properties. Prior work had shown a correlation of optical properties with wait time after mixing. The data are listed in Table 25.

From the data in Table 25, it can be seen that, as the concentration of aluminum pigment increases, both absorptance and emittances decreases. The best coating contained 30-percent Alcan 462 aluminum pigment with $\alpha_s = 0.86$ and $\epsilon_{TH} = 0.58$. The optical properties of the coatings were not significantly affected by a 24-hour aging process prior to application.

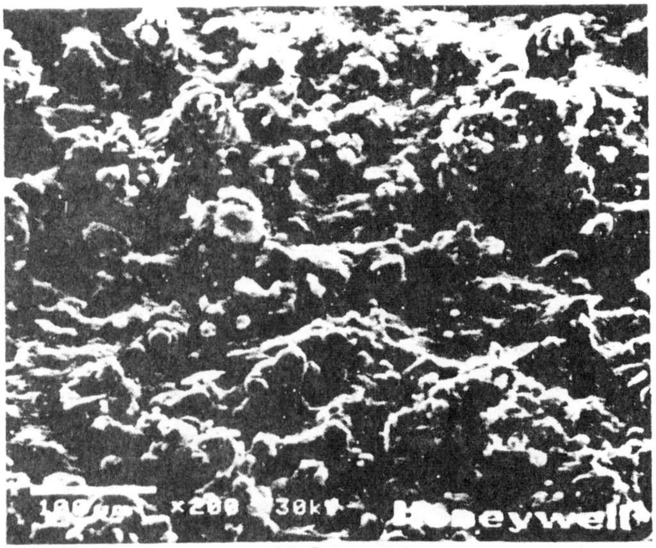
Table 25. Effect of Solution Aging on the Optical Properties of Thickness Insensitive 30 PVC F-6331/SR-125/Alcon Pigment Coatings

Type, Alcan	Pigment Particle Size (μm) (avg)	Concentration (% by wt.)	Time After Mixing, Absorptance, Emittance			
			1 Hour		24 Hours	
			α_s	ϵ_{TH}	α_s	ϵ_{TH}
769	10	10	0.91	0.74	0.89	0.70
		15	0.90	0.71	0.88	0.68
		20	0.88	0.67	0.88	0.70
		25	0.87	0.66	0.86	0.69
		30	0.85	0.68	0.88	0.69
565	20	10	0.89	0.70	0.90	0.71
		15	0.90	0.69	0.89	0.66
		20	0.87	0.64	0.89	0.66
		25	0.85	0.62	0.89	0.65
		30	0.86	0.62	0.88	0.64
462	40	10	0.89	0.66	0.90	0.67
		15	0.89	0.63	0.90	0.66
		20	0.88	0.61	0.89	0.62
		25	0.87	0.62	0.87	0.59
		30	0.86	0.58	0.85	0.56

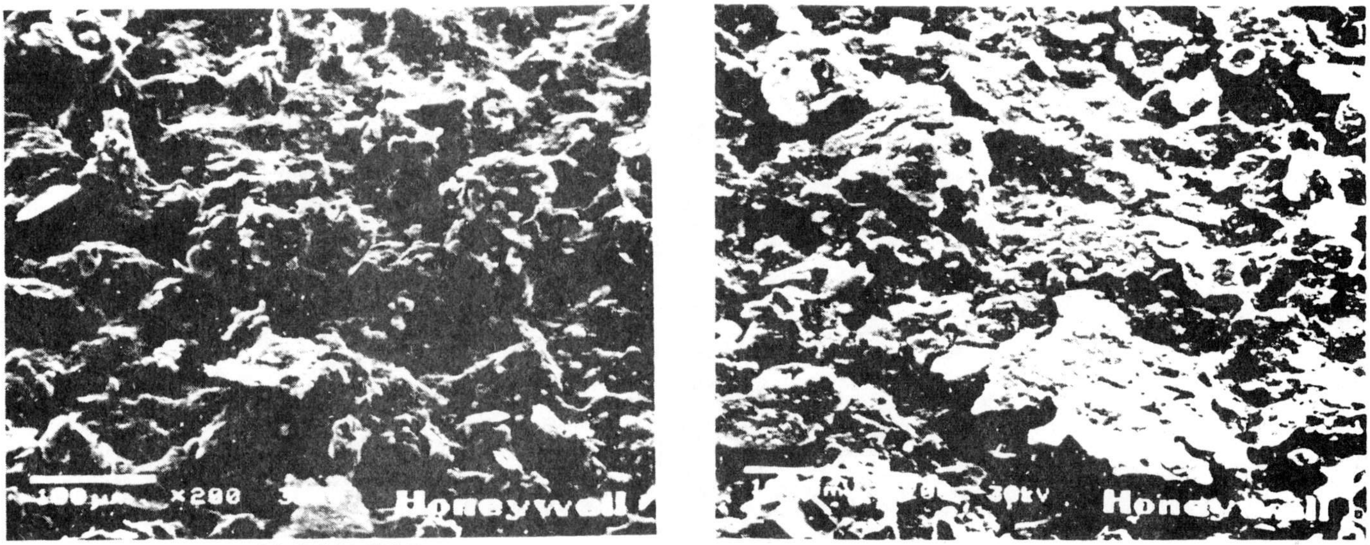
The SEMs of these paint coatings are shown in Figure 17. Patterns of surface structures observed in the flake coatings without F-6331 black pigment replicate the coatings with aluminum flakes combined with F-6331 pigment. The larger flakes still give flatter coatings with a lower emittance. The small F-6331 pigment particles can be seen spread over the aluminum flake surfaces.

The optical properties of Alcan leafing flakes were not as good as the previously made paint coating using Alcoa 2468 aluminum flake, which had an α_s of 0.89 and ϵ_{TH} of 0.31. The SEM of an Alcoa 2468 aluminum flake, 30 PVC F-6331/SR-125 paint coating was taken for comparison and is shown in Figure 18.

Figure 18 shows that the 2468 flakes give a very flat coating surface. The flake sizes are relatively uniform and approximately 50μm in size. Alcoa 2468 aluminum flake appeared to be the best pigment tested. The paint development work was thus concentrated on this as the primary high-reflecting pigment.



ALCAN 769



ALCAN 565

ALCAN 462

Figure 17. SEM of F6331/SR-125/Leafing Aluminum Flakes Coatings

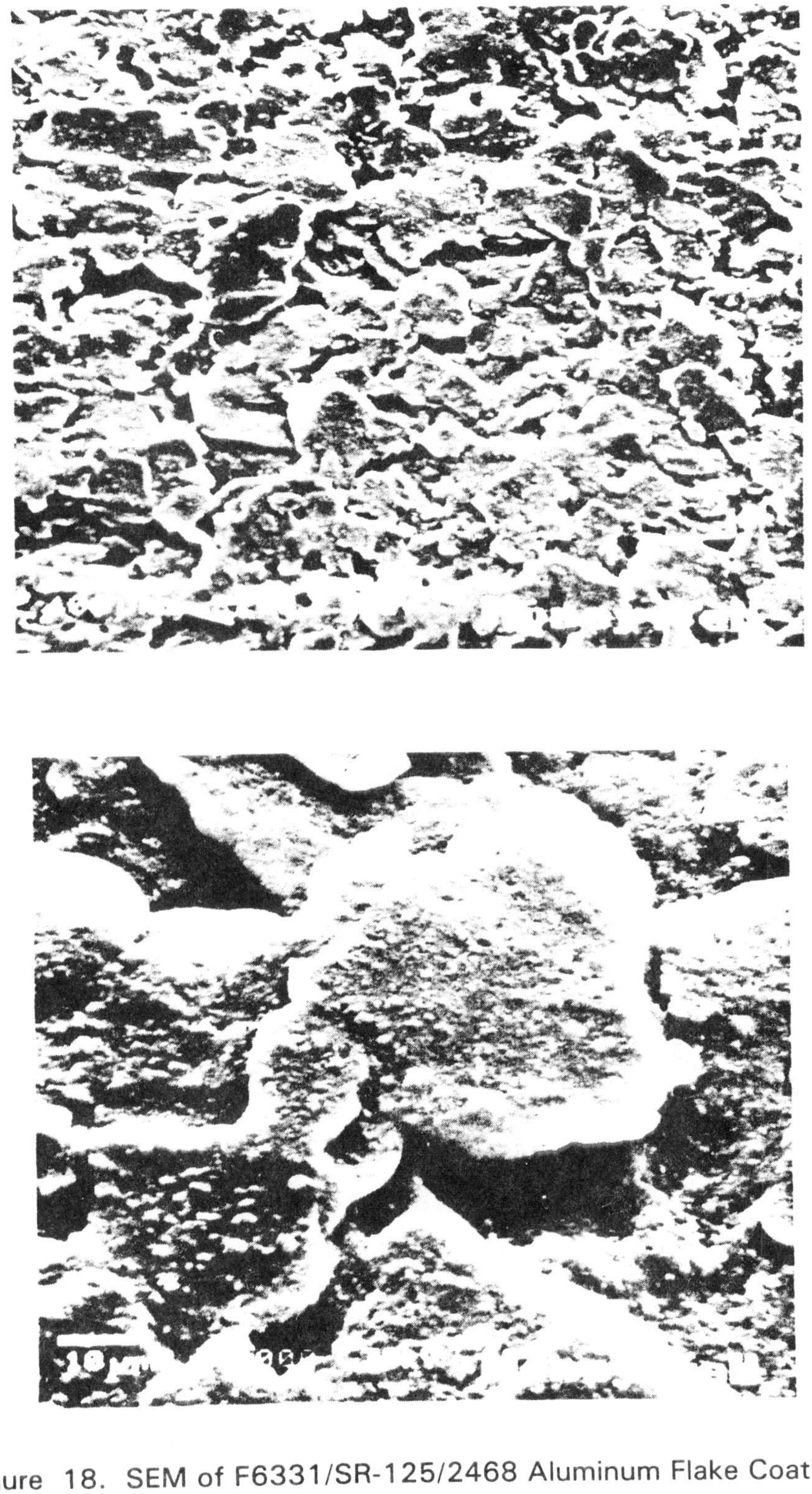


Figure 18. SEM of F6331/SR-125/2468 Aluminum Flake Coating

Binders — Attempts to alter silicone binders by catalyzing were only partially successful. A degree of cure at room ambient temperatures was achieved, but the solvent resistance was insufficient for practical purposes. (See subsection, "Thickness-Sensitive Selective Paint Coatings, Binders".) Also, as previously described, the Cargill 6247 silicone-modified epoxy resin was selected for further development, especially for TISP coatings.

Experimental Paint Coatings — The lack of repeatability of optical properties for TISP coatings continued to be a problem as various coatings were formulated and evaluated. A study was initiated to determine the effect of aluminum and black pigment concentration on the optical properties of coatings.

A 20 PVC F-6331/6247 coating was prepared by ball milling. Paint coatings with lower pigment concentrations were prepared by adding quantities of 6247 binder to quantities of the 30 PVC coating. Pigment concentrations were varied from 10 to 30 PVC, in 5-PVC increments. To each of these coatings was added various quantities of Alcoa 2468 aluminum pigment. Aluminum pigment concentrations varied from 0 to 30-percent aluminum solids, based on coating solids. The series of paint coatings was mixed, spray-applied to aluminum panels, cured, and the optical properties then measured. Results are listed in Table 26.

Table 26. Effect of Pigment Concentration on the Optical Properties of Thickness Insensitive Selective Paint Coatings

2468 Aluminum Pigment (% by wt.)	PVC of F-6331/6247 Paint Coating									
	10		15		20		25		30	
	α_s	ϵ_{TH}	α_s	ϵ_{TH}	α_s	ϵ_{TH}	α_s	ϵ_{TH}	α_s	ϵ_{TH}
0	0.90	0.49	0.92	0.60	0.89	0.38	0.89	0.40	0.89	0.42
10	0.84	0.45	0.83	0.37	0.84	0.41	0.85	0.44	0.85	0.40
20	0.76	0.43	0.77	0.42	0.83	0.39	0.88	0.41	0.74	0.33
30	0.70	0.37	0.69	0.35	0.73	0.32	0.69	0.37	0.69	0.30

The coatings without aluminum flake exhibited varying degrees of show-through, and, thus, do not serve as a coating standard of reference. Coatings with 10 to 30-percent 2468 aluminum flake show emittance of $\epsilon_{TH} = 0.30$ to 0.45 and solar absorptance $\alpha_s = 0.88$ to 0.69. The most selective coating contained 20-percent aluminum flake in 25 PVC F-6331/6247, where $\alpha_s = 0.88$ and $\epsilon_{TH} = 0.41$. There appeared to be no trend in the data leading to this particular combination. However, further effort to determine the effect of aluminum flake concentration should provide clues to the trends in optical properties.

Quantities of 30 PVC F-6331/SR-125 paint coatings were combined with Alcoa 2468 aluminum flake. In all, eight coatings were prepared, varying in aluminum flake content from 20 to 100 percent, based on pigment solids. The coatings were mixed for 10 minutes on a Red Devil paint shaker and immediately spray-applied to aluminum panels, air-dried 30 minutes, cured for 1 hour at 500°F, and measured for optical properties. Selected coating solutions were allowed to age for 1, 2, and 3 weeks. Aged coatings were reagitated and applied, cured, and measured, as previously described. The data are recorded in Table 27.

From Table 27 it can be seen that solar absorptance peaks at 35 percent, remains essentially the same to 60 percent, and then drops rapidly at 100-percent aluminum pigment concentration initially (no aging of the solution). Coating solution aging for 1 week shows a dramatic increase in solar absorptance for the coating containing 100 percent, but essentially no change for coatings containing 40- and 50-percent aluminum pigment.

Table 27. Effect of Solution Aging on the Optical Properties of Thickness-Insensitive 30 PVC F-6331/SR-125/2468 Coatings

Aluminum Flake, (% by wt.)	Time After Mixing, Absorptance, Emittance							
	Initial		1 Week		3 Weeks		6 Weeks	
	α_s	ϵ_{TH}	α_s	ϵ_{TH}	α_s	ϵ_{TH}	α_s	ϵ_{TH}
20	0.78	0.58	-	-	-	-	-	-
25	0.66	0.50	-	-	-	-	-	-
35	0.90	0.62	-	-	-	-	-	-
40	0.89	0.50	0.89	0.45	-	-	-	-
45	0.90	0.58	-	-	-	-	-	-
50	0.88	0.35	0.88	0.37	-	-	-	-
60	0.89	0.39	-	-	0.89	0.37	0.89	0.46
100	0.56	0.25	0.85	0.32	0.87	0.37	-	-

Coating Aging Effects — These differences can be explained by aluminum flake wetting, as previously discussed. Lot-to-lot changes in the surface area of aluminum pigments could explain why material used now does not replicate the properties of material used several years ago. Attempts to remove film from the aluminum flakes and increase agitation prior to application failed to increase absorptance of freshly mixed coating.

After 3 weeks of aging, the coating containing 60-percent aluminum pigment remained essentially the same as it was initially. However, after 6 weeks of aging, the emittance of this coating increased significantly. The data from Tables 20 and 27 suggest that aging these coatings for 24 hours is necessary to achieve a high solar absorptance, while yet maintaining a low thermal emittance. Coatings must be used within about 3 weeks after combining the aluminum pigment and TSSP coating before the film shows a degraded thermal emittance.

These data further suggest that a two-component coating, one component being the aluminum pigment and the other component the TSSP coating, would provide a means of achieving a long pot life, TISP coating replicating the original work. It was concluded at this time that the optical goal of $\alpha_s = 0.90$ and $\epsilon_{TH} = 0.15$ was unrealistic for the conventional concept.

Coating Stabilizers – To avoid the need to age the coatings 24 hours prior to use, another approach was investigated. This approach attempted to orient the aluminum particles parallel to, but slightly below the coating's film surface by using coating stabilizers. Manufacturers of coating stabilizers were contacted and various candidate materials identified (Table 28).

Table 28. Coating Stabilizer Candidates

Manufacturer	Coating Stabilizer	Description
Degussa	R-972 A-200	Silica Silica
Hercules	N-22	Ethyl cellulose
Tenneco	Nuosperse 700 Nuosperse 657	
Tray chemical	Troykyd 98C Troykyd 42BA	

The Degussa silicas were selected for screening tests and incorporated in 30 PVC F-6331/6247/2468 coatings with varying amounts of aluminum pigment. The concentration of stabilizer was 1 percent, based on the coating weight for the R-972 and A-200 materials. Coatings were mixed, spray-applied to aluminum substrates, cured, and measured for optical properties (see Table 29).

From Table 29 it can be seen that some improvement in solar absorptance was gained by using the R-972 stabilizer. However, as the concentration of aluminum pigment was increased, the thermal emittance of coatings containing the R-972 stabilizer essentially remained unchanged and solar absorptance decreased. Thus, the use of stabilizers had a small, specific beneficial effect, but were not considered for further development.

ENGINEERED-PIGMENT APPROACH

The probability of meeting program goals is an on-going process of state-of-the-art evaluation and risk assessment. Because of the difficulty in achieving repeatable optical data from experimental TISP coatings, another approach was conceived and a limited investigation was pursued to provide base line data on the concept and establish a potential backup for the conventional approach.

Table 29. Effect of Degussa Stabilizers on the Optical Properties of Thickness-Insensitive 30 PVC F-6331/6547/2468 Coatings

Aluminum Flake (% by wt.)	Stabilizer Used					
	None		R-972		A-200	
	α_s	ϵ_{TH}	α_s	ϵ_{TH}	α_s	ϵ_{TH}
5	-	-	0.94	0.72	-	0.72
10	-	-	0.92	0.68	0.80	0.62
20	0.78	0.58	0.88	0.61	-	0.57
30	-	-	0.88	0.57	-	0.36
40	0.89	0.50	0.84	0.53	0.58	0.42
50	0.88	0.35	0.84	0.52	-	0.43
60	0.89	0.39	0.81	0.46	-	0.37

The pigment engineering approach essentially attempts to provide control of all coating ingredients in the liquid, as well as the film phases of the coating. The coating would be composed of a combination of F-6331 pigmented paint coating and TSSP-coated aluminum foil particles.

Aluminum foil was coated on both sides with 30 PVC F-6331/6247 to provide α_s = 0.90 and ϵ_{TH} = 0.26. It was then punched to get rectangular particles of 0.004 inch by 0.008 inch. These particles were combined with 30 PVC F-6331/SR-125 paint coating, spray-applied to aluminum panels, cured, and the optical properties measured. Optical properties varied from α_s = 0.89 and ϵ_{TH} = 0.58 to α_s = 0.90 and ϵ_{TH} = 0.80. It is believed that further improvements in this system would significantly improve thermal emittance. Further effort on TISP coatings should be directed at the engineered-pigment approach.

Section 4
Conclusions

THICKNESS-SENSITIVE SELECTIVE PAINT COATINGS

Materials

Pigment — Ferro F-6331 was the primary pigment of choice for solar-selective paint coatings. A good backup material is Harshaw L-5503-5 and 7890 pigments. The primary pigment was the material of choice because of good optical properties, reasonable cost, availability, particle size, compatability with binder systems, and absence of strategic materials in its composition. The Meteor 7890 backup material contains chromium, a strategic material, but is acceptable in all other areas mentioned above, while the L-5503-5 is somewhat deficient in absorptance but has the advantages of having no strategic materials and high viscosity in coatings.

Binder — General Electric SR-125 silicone binder was selected as the material of choice where optimum optical properties, UV stability, and high-temperature resistance are of primary concern. It is moderate in cost, readily available, and compatible with pigments, but requires an elevated temperature curing. High-intensity, SCR-controlled infrared radiation may be used to quick-cure the material.

Cargill 6247 silicone-modified epoxy binder was selected as the material of choice where optimum abrasion resistance and room ambient cure are the primary concern. It is moderate in cost, readily available, and compatible with pigments.

Paint Coating — The optical properties of the paint coating were maintained at $\alpha_s = 0.90$ and $\epsilon_{TH} = 0.10$, while costs were held to $0.01/ft^2. The physical properties of the coatings were essentially maintained from those of dip coating throughout the various processes of application, spray, roll, and gravure coating. Silicone-based coatings applied by the gravure process were more susceptable to damage from abrasion than when applied by other processes.

Solar Absorptance Enhancement Coating — The use of FEP Teflon (FEP-120) as an AR coating to enhance the solar absorptance by 3 to 4 percent was demonstrated. The concept was not pursued due to the effort needed on other parts of the development, but remains as a significant accomplishment in selective-paint coating technology.

Solar Tape — The solar tape concept became a reality through the development of high-speed coating procedures using the gravure process. Production feasibility was demonstrated by the successful coating of 10,000 ft^2 of tape. The best way to produce the tape at the lowest cost was to use gravure coating equipment to apply the selective black paint coating, and roll laminating/coating equipment to apply the adhesive, release liner and protective plastic film. High-quality, high-performance, low-cost solar tape was easily produced, yet some room still remains for further improvement. Optical properties for the 28 PVC F-6331 silicone system (SR-125) reached $\alpha_s = 0.90$ and $\epsilon_{TH} = 0.07$, and for the silicone-epoxy (6247) system $\alpha_s = 0.90$ and $\epsilon_{TH} = 0.15$. Cost of the solar tape was \$0.22/ft^2 at 10,000 ft^2. Projected costs for 1 million ft^2 were estimated at \$0.15/ft^2. These costs included all materials, plus the cost of manufacturing.

Coating Processing (Paint Milling)

The most promising method of milling solar-selective paint coatings was found to be the sand-milling procedures. Sand milling was determined to be cost effective for quantities larger than laboratory-size batches, reasonably noncontaminating from an optical standpoint, while appearing to enhance the distribution of pigment particles and improve pigment wetting.

Coating Application

The solar-selective paint coatings developed to date were successfully applied by dip, spray, roll, and gravure coating procedures to achieve good optical selectivity.

THICKNESS-INSENSITIVE SELECTIVE PAINT COATINGS

Conventional Approach

Metallic Pigment — Of all the metallic pigments investigated, the aluminum pigments show the most promise. Leafing aluminum pigments were better reflectors than non-leafing types. Large flakes were also found to be more reflective than small flakes. The most promising aluminum flake evaluated to date was Alcoa 2468, although other aluminum flakes may perform as well under certain conditions.

Binder — The binder that showed the most promise from all standpoints was a silicone-modified epoxy designated 6247 by its manufacturer, Cargill. This binder was found useful for both the TSSP coatings, as well as TISP coatings. Where greater exterior durability is desired, acrylic or aliphatic urethane binders may also be used with suitable formulation changes.

Paint Coating — The current state of the art for TISP coatings provides coatings that are somewhat sensitive to the method of application, and to the time after the aluminum flakes and paint coating are mixed. Optical performance of the TISP coatings are optimum between 1 day and 3 weeks after the mixing of the aluminum flakes and paint coating, and applied in thin coats rather than thick coats.

Engineered-Pigment Approach

This approach apears to offer better overall control of TISP coating materials. Use of TSSP coated foil as the high-reflecting pigment should provide more solution stability after mixing, larger individual reflectors, and better control of the coating's optical properties.

Section 5
Recommendations

THICKNESS-SENSITIVE SELECTIVE PAINT COATINGS

Materials

Pigment — Ferro F-6331 is the first choice, with Harshaw L-5503-5 and Meteor 7890 as the alternatives.

Binder — Either General Electric SR-125 silicone or Cargill 6247 silicone-modified epoxy are recommended. The choice of which resin to use will depend on which area is emphasized in the application: UV resistance, abrasion resistance, and/or high-temperature resistance (see Section 4, Conclusions).

Paint Coating — The combinations of F-6331/SR-125 or F-6331/6247 provided the best overall properties. The PVC can be varied between 28 to 30 to meet specific requirements.

Solar Tape — The solar tape should be constructed as follows:

Protective film:	1-mil Mylar polyester
Paint:	28 PVC F-6331/SR-125 or 28 PVC F-6331/6247
Aluminum foil:	2-mil Reynolds No. 8079 (1183-TO) or equivalent
Adhesive:	1-mil 3M Scotchgrip 4914 acrylic
Release liner:	90-lb H.P. Smith 8514 (lower weight material can be used for web sizes greater than 13 inches)

Coating Processing (Paint Milling)

The sand-milling procedure is recommended for solar paint coating production. Care must be taken to select sand quality and cleanliness to minimize coating contamination.

Coating Application

Each process was found to have advantages and disadvantages, but, with proper controls, could be used to achieve solar-selective coatings. Guidelines, with optical properties achieved to date are listed in Table 30.

Table 30. Coating Processes Performance Summary

Process	Size Production (Typical)	Range		Best Obtained	
		α_s	ϵ_{TH}	α_s	ϵ_{TH}
Dip	Small-Medium	0.88 to 0.90	0.10 to 0.14	0.90	0.06
Spray	Small-Large	0.91 to 0.93	0.13 to 0.32	0.92	0.13
Roll	Small-Medium	0.86 to 0.89	0.09 to 0.14	0.88	0.14
Gravure	Medium-Large	0.90 to 0.92	0.07 to 0.20	0.90	0.07

THICKNESS-INSENSITIVE SELECTIVE PAINT COATINGS

Metallic Pigment

Alcoa 2468 is the choice of aluminum pigments from among those evaluated.

Binder

Of the binders evaluated with room ambient cure, Cargill 6247 silicone-epoxy provided the best overall performance.

Paint Coating

The best overall paint coating combination was with 30-percent solids, 30 PVC F-6331/6247/60-percent Alcoa 2468 with 0.25-percent Degussa R-972 stabilizer.

Engineered-Pigment Approach

Further effort with TISP coatings should be directed at the engineered pigment approach. This approach offers the greatest chance of success for TISP coatings.

Section 6
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