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STATE OF CALIFORNIA
DEPARTMENT OF TRANSPORTATION
DIVISION OF CONSTRUCTION
OFFICE OF TRANSPORTATION LABORATORY

June 1979

TL No. 657320

Mr. C. E. Forbes
Chief Engineer

Dear Sir:

I have approved and now submit for your information this final research project report titled:

EVALUATION OF SOLAR SCREENS

Study made by ..... Enviro-Chemical Branch

Under the Supervision of ..... Earl C. Shirley, P.E. and Roy Bushey, P.E.

Principal Investigator ..... Joe Palen

Assisted by ..... Paul Benson, P.E.

Very truly yours,

NEAL ANDERSEN
Chief, Office of Transportation Laboratory

Attachment

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INTRODUCTION

It has been estimated that between 25 and 50 percent of an office building's annual energy requirements is used to exhaust the excess solar heat coming in through windows. When properly used, solar shading materials will not only reduce this solar heat gain, but can also add to the "insulative value" of the window, and thereby cut down on the heating requirements as well. Although the function of these materials is relatively straightforward, the calculation of their potential energy savings is not.

It should be realized that the field of solar energy is still in its infancy, and there is some question as to the best procedure for evaluating solar screens. There are many interrelationships between the sun-window orientation, the weather conditions, and the properties of the building itself, all of which have an effect on the solar screen's operation. Even under a given set of conditions, solar heat can come in by different mechanisms (direct transmission, convection and radiation) each of which is difficult to quantify accurately.

This report introduces the basic principles of solar energy and heat transfer, showing how these concepts are used in the evaluation and testing of solar shading systems, discussing the limitations of these tests, and reviewing some of the past and ongoing research. Also included are a number of specific research recommendations, so that shading materials can be more effectively evaluated in the future.

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Although the energy saving potential is usually the main reason for purchasing shading materials, there are a number of other parameters which should be considered. Solar lighting, aesthetics, ease of cleaning, durability, building characteristics, etc., all may be of relevance in determining the optimal material and are also discussed in the report.

The main body of this report is organized into three sections. The first section introduces many of the basic parameters used to evaluate window systems, using the current state-of-the-art. The second section describes the methodology and results of specific tests done at the Transportation Laboratory on a limited number of screening products. The final section discusses some of the general considerations relevant to the evaluation of all the various types of shading strategies available today, drawing heavily on information obtained in the literature search.

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BACKGROUND

This section is meant as a quick introduction to some of the more common parameters used for the evaluation of solar screens. It should be realized that there are many relevant factors not presented here, and many inherent limitations to those that are.

The main function of solar shading material is to reduce the solar radiation entering through windows. Solar radiation enters in two ways since window glass both transmits and absorbs solar radiation. The radiation transmitted through the glass may be either direct radiation or diffuse (sky) radiation. This radiation, being radiant heat, is either absorbed or reflected by the materials and objects it strikes inside the building. Those materials which absorb radiant heat contribute to the heat load inside the building by convection and radiation of the temporarily stored heat. The radiation absorbed by the window glass is also temporarily stored heat. In the case of the window, however, the stored heat can flow through radiative or convective exchanges at either the indoor or outdoor window surface. The quantity exchanged at the indoor surface adds to the building heat load.

For the purposes of this highly simplied discussion, diffuse (sky) radiation, which is usually less than 10% of the value of direct radiation will be ignored. Also, the effect of the heat absorbed by and released from the window glass itself will be ignored. This value is always fairly small and although it may exceed the value for direct radiation in the morning and late evening, during the period when solar radiation is contributing heavily to the heat load, the value is only about 10-20% of the value

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for direct radiation. Ignoring these values allows solar heat gain (SHG) to be equated to transmitted direct solar radiation. This is equivalent to the direct solar radiation (I_D) in BTU/hr/sq.ft. incident upon the window multiplied by a value of transmittance for the particular type of glazing and angle of incidence (the transmittance value for a single thickness of common window glass with radiation at normal incidence is 0.87). The resulting value is termed the solar heat gain factor (SHGF).

Although the ignored values are important in estimating heat load in a building, their absence in comparing solar shading material is relatively inconsequential since all the values are proportional to the area of window exposed to radiation. For this reason, the concept of shading coefficient (SC) is important. The shading coefficient is the amount of radiant heat that passes through a shaded window compared to the radiant heat that passes through a single pane of common double-strength window glass. The lower the shading coefficient, the more effective the shading system is in blocking solar radiation.

Another function of solar shading material is to reduce the rate at which heat flows through the window directly to or from the outside atmosphere. This property is commonly called the thermal transmittance (U) and has units of (BTU/hr/ft^2/°F). It is approximately equal to the inverse of the "R value", which is often used to evaluate insulation. A low value of U is desirable for a window-shading system. The thermal transmittance is usually thought of as being completely independent from the solar heat gain although in reality this is not entirely true. However, this makes it conceptually and mathematically much easier to deal with.

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For comparative purposes, the heat gain through a shading system can then be calculated by:

$$\text{Heat Gain} = (U)(T_o - T_i) + (SHGF)(SC)$$

where: U, SHGF, and SC are previously defined,
T_o is the outside ambient temperature (°F), and
T_i is the interior temperature (°F).

For comparative purposes the energy savings from a particular shading system can be computed using the heat gain formula as follows:

1) Determine solar declination by:

$$DECL = 23.45*\sin(0.986*(JUL-80))$$

where: JUL = Julian Day (1 thru 365)

2) Determine solar altitude by:

$$ATL = 90 - \cos^{-1}(\sin(LAT)*\sin(DECL) + \cos(LAT)*\cos(DECL)*\cos(HRAN))$$

where: LAT = latitude
HRAN = hour angle
= 15*TIME-180
TIME = military solar time (1:00 PM = 1300)

3) Determining total window area affected by direct solar radiation.

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4) Reduce window area for shading by overhangs, louvers or window inset as function of ALT and window geometry.

5) Determine SHGF from American Society of Heating, Refrigeration and Air conditioning Engineers' Handbook (ASHRAE) tables using ALT.

6) Determine heat gain per ft^2 per hour using U, SC, T_o, T_i and SHGH.

7) Multiply by adjusted window area.

The annual energy savings can be calculated either by using average values for the outside temperature, sun angle, and SHGF (this method involves many gross simplifications and is generally inaccurate), or devising a computerized simulation model which will integrate steps 1 through 7 over daily and annual cycles of temperature and sun angle.

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TEST METHODOLOGY AND RESULTS

A series of tests was conducted by the Transportation Laboratory in an attempt to evaluate the efficiency of a variety of solar screening devices for windows. The devices tested were provided by the Californa Energy Commission and represented a sampling of currently available commercial brands.

When devising a test for shading devices, it is desirable that the test be representative of field performance, repeatable and economical. A number of testing techniques were evaluated using the above criteria.

The first technique tried was to make a number of insulated boxes, attach the screening material to the open face, place them in the sun, and check the temperature. The one with the least rise in temperature would be judged the best device. This type of test is an oversimplification of actual performance, however.

It is impossible to determine if the temperature rise is due to the device letting in more sun (high SC) or letting out less heat (low U). Mathematically, this is expressed by

$$\text{heat transfer} = Q = SC(SHGF) + U(T_o - T_i).$$

At any given instant, the system is in approximate equilibrium, so

$$Q = 0 = (SC)(SHGF) + U(T_o - T_i)$$

$$T_i = T_o - \frac{(SC)\ (SHGF)}{U}$$

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For any given set of environmental conditons, SHGF and T_o are fixed, so the internal temperature (T_i) is directly related to the ratio SC/U. This means that two screening devices would produce the same temperature by having the same SC/U ratio, even though one may be very good (i.e., have a low absolute value for both SC and U), while one may be poor (high SC and U value). Analysis of this type of experiment would be further complicated by the fact that when the boxes heated up above the outside ambient temperature, a substantially smaller proportion of the solar radiation would be transmitted inward via radiative and convective heating of the window pane (this differs from a real office building where this heat would normally be exhausted by the air conditioning).

A number of other relatively inexpensive but more effective tests were done by the Transportation Laboratory. They are described below.

Visible Transmittance - The visible light spectrum approximately coincides with the peak of the solar spectrum. Consequently, visible transmittance generally has a good correlation with solar transmittance which comprises a major portion of the shading coefficient. It also is the best indication of the aesthetic (i.e., ability to see outside) and solar lighting potential, which are the primary functions of a window in the first place.

Tests were conducted in the light tunnel of the Transportation Laboratory using a tungsten filament light source. The light source was placed at a distance such that a 0.02 steradian view factor (approximately the same as for the sun) was extended at the photo detector. The photo detector

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had a peak spectral specificity of 0.58 μ, slightly higher than that for the human eye (no adjustments were made to correct for this). Results given in percent visible light transmitted through the shading device are shown in Table 1.

Thermal Transmittance - An experiment to evaluate the thermal transmittance (U) of the shading materials used in Table 1 was also conducted. The testing device consisted of a 2 ft^3 plywood box surrounded by 3 inches of urathane insulation. One face was left open with mounting brackets to affix the shading device and glass plate with a 1/2 inch gap between the two. The heating element was a 1 ohm hollow resistor hooked up to a variable power supply. A low power fan was adjusted such that it barely counteracted the natural convective forces in the box. Additionally, an air beam splitter was used to spread the heat horizontally. This procedure was marginally successful: the glass surface temperature was not found to vary more than ±1.5°C once the system was equilibrated. No attempt was made to determine the fan's wind speed (although it was barely perceivable against the skin). It is thought that this adequately simulated interior building conditions.

The testing device was placed in an environmentally controlled room which was used primarily as a heat sink. This room was kept at a humidity of 3 to 10% to avoid condensation problems. Each shading system was sealed to the box with silicon gel to minimize infiltration problems. Thermal measurements were made with a 12 channel continuous recording device using 29 gage thermocouple wire. Eight thermocouples were placed in an array approximately 1/2 inch from the interior glass surface to test for thermal stratification. The remaining 4 were used to measure the ambient conditions.

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Table 1: Visible Light Transmittance of Selected Solar Screen Materials
(Percent Transmitted)

Angle (In degrees)	MATERIAL * A	B	C	D	E	F	G	H
0°	89.1	19.0	35.7	53.7	26.4	13.8	24.1	31.4
2.5			31.8	51.1	24.1	11.9	24.1	
5.0			28.3	48.2	21.2	10.3	24.1	
7.5			24.4	45.0	18.6	8.4		
10.0	89.1	19.0	20.9	42.4	16.1	6.4	23.8	30.6
12.5			16.7	39.9	13.5	4.5		
15.0			13.2	36.7	10.9	2.9	23.8	
17.5			9.0	33.8	8.0	1.6		
20.0	89.1	18.6	5.1	30.9	5.5	1.0	23.8	29.8
22.5			1.6	27.7	2.6	1.0		
25.0			1.0	24.4	1.3		23.5	
27.5			1.0	20.9	1.3			
30.0	88.7	18.6	1.0	17.4	1.3		23.2	
32.5				13.2				
35.0				9.3			22.5	
37.5				4.5				
40.0	87.8	18.3		1.6			21.9	
45.0	87.1			1.3			21.2	
50.0	85.2	17.7		1.3			19.9	
55.0	82.6	17.4		1.0			18.6	
60.0	79.1	16.4		1.0			16.4	

*All materials were provided by the California Energy Commission. Brand name of the double pane configuration was unknown.

A - 3/16" clear flat plate glass (not double strength)

B - " " " " " with 3M Bronze film on interior surface

C - " " " " " with anodized black "Koolshade" 23 louvers/in.

D - " " " " " with anodized black "Koolshade" 17 louvers/in.

E - " " " " " with Kaiser aluminum "Shadescreen", gr

F - " " " " " with Kaiser aluminum "Shadescreen", bla

G - " " " " " with "Selenger" fiberglass sunscreen, b

H - 1/4" double pane glass with 1/4" air space, Silver interior surface coating

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Each run took approximately 4 hours to equlibrate, so only one device was tested each day. Due to limited project funds only a single run on each material could be made once the device was calibrated. We were not able to determine the variation in U values with different wind speeds, temperature gradient and direction of heat flow as had been originally planned. It should be noted that the values presented here were not tested under a 7.5 mph exterior wind speed, and, therefore, are generally lower than those presented in the ASHRAE handbook. Results are given in Table 2.

Shading Coefficient - The correct assessment of the shading coefficient involves the construction of a relatively sophisticated testing device not presently feasible under the financial limitations of this project (one testing device and peripheral equipment has a shipping weight of 2.5 tons). Therefore, values presented here were obtained from the literature. Materials tested with a known (state of the art) experimental technique are marked with an asterisk. Unmarked materials do not necessarily represent inaccurate values (see Table 2).

Accelerated Weathering - Two instruments were used to simulate weathering effects. An Atlas Type W Weatherometer was used to induce environmental degradation with the exterior screening materials using alternate cycles of heat, moisture, and intense light (with approximately the same spectrum as natural solar radiation). The interior shading material (solar film bonded to the interior of a glass surface) was placed in an Atlas FAD-R Color Fadeometer, which produces cycles of intense UV radiation.

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Table 2: SC and U Values for Selected Materials

Material	Shading Coefficient (SC) 10°	20°	30°	40° **	Thermal Transmittance(U) (BTU/hr°F Ft^2)
A*	1.00	1.00	1.00	1.00	1.03
B	0.29	0.29	0.29	0.29	.98
C*	0.40	0.27	0.17	0.18	.93
D*	0.51	0.42	0.31	0.18	.91
E*	0.41	0.33	0.23	0.20	.90
F*	0.43	0.31	0.18	0.14	.90
G*	0.32	0.32	0.32	0.31	.86
H	0.30	0.30	0.30	0.30	.63

*Values were obtained using a known standardized experimental procedure.

**Angle of light source from line perpendicular to shading system. Properties are assumed constant for angles greater than 40°.

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Past experience has shown that one month in each device is approximately equal to one year in an average California environment. Samples were tested for 6 months.

Bronze Solar Film - No appreciable chromatic distortion was noted. Sample began to peal and crack around edges, indicating that there could be potential bonding problems.

Koolshade Solar Screens - No weathering effects were detected.

Kaiser Shadescreen - Black material showed no weathering effects. Green material showed slight oxidation of finish.

Selenger Solar Screens - Eight different colors of this material were tested. White, tan, grey, and charcoal samples showed noticeable fading. All samples exhibited some warping and brittleness, although not enough to induce breakage.

Double Paned Configuration - No sample was provided of suitable size to be utilized in weathering tests.

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DISCUSSION OF SHADING STRATEGIES

Only a limited number of materials were submitted to the Transportation Laboratory for evaluation. For the sake of completeness, a brief discussion of all of the major types of solar shading strategies is included. This draws heavily on information obtained from the literature and other research institutions, as well as our own findings.

No attempt has been made to quantitatively determine the annual energy savings potential of each material. This would depend on a great number of factors (local weather, window orientation, building parameters, etc.) and would necessitate the use of a computer simulation program not currently available. Some attempts have been made to do this using numerous simplifying assumptions and average values which may compromise the credibility of the results. They seem to indicate that louvered screens, fiberglass screens, and internal films (similar to the one evaluated here) all yield comparable annual energy savings.

OVERHANGINGS AND SIDE FINS - These are probably the most effective form of shading device because their large mass and low thermal conductivity causes them to essentially "block" all the incident solar radiation. They also can be designed to allow solar input at low sun angles when solar heating is needed (such as winter mornings). However, these devices must be incorporated into the artchitectural framework of the building and are not practical for retro-fit operations.

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AWNINGS - These differ from overhangings in that they transmit or re-radiate a significant portion of the solar input. Awnings have large wind loadings and as such, are commonly used only on the bottom floors.

EXTERIOR SUN SCREENS - These screens block the majority of the incident solar radiation, but much of this absorbed heat is dissipated into the air space between the screen and the window and can eventually end up inside. Therefore, any given sun screen will generally be more effective when mounted as far away from the window surface as possible.

There are two basic types of exterior sun screens: directional and non-directional. Directional sun screens consist of small metal louvers oriented such that they will block most of the solar ratiation at high sun angles, while transmitting a greater portion at lower sun angles. Thus, the SC value for these types of shading devices varies with the sun angle. This has the advantage of keeping out most of the midday solar heat, while admitting some solar heat in the mornings and winter (similar to overhangs). There are currently two major manufacturers of this type of screen, "Kaiser Shadescreen" and "Koolshade". Both of the "Kaiser Shadescreen" samples tested were made of stamped alluminum with the only physical difference being their color. Although the Kaiser products are considerably lighter than "Koolshade", they are not as strong, have a greater wind loading, and appear to be somwhat less resistant to corrosive environments. The two "Koolshade" samples tested were both anodized black, one with 17 louvers/in. and one with 23 louvers/in. Although their solar and thermal properties are similar to the Kaiser products (see Table 2), they allow greater visibility.

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Generally, the greatest instantaneous heat gains occur in the afternoon on the west face of a building. Therefore, it is recommended that the materials with higher shading coefficients (Kaiser Black and Koolshade 23) be used on west windows. Depending on the heat loading of the building, it may be desirable to use a material with a relatively lower shading coefficient (Kaiser Green or Koolshade 17) for south and east windows. North windows in the temperate zone should not be covered at all.

NON-DIRECTIONAL SUN SCREENS - These can be made of fiberglass or metal, with only the fiberglass screens being considered here. Fiberglass screens come in a variety of different colors, with the darker colors generally exhibiting lower shading coefficients. Their main advantages over the louvered screens is that they have good visibility at all angles and a slightly lower thermal transmittance. They are also not expected to deteriorate significantly in corrosive environments, since most of their degradation is apparently due to UV radiation. These screens might be expected to last longer in coastal areas then they would in mountainous areas (larger percentage of UV radiation).

MULTIPLE GLAZED SURFACES - These usually consist of two or more panes of glass mounted in a special frame. Often, glass-metal-plastic laminates are used to obtain special structural or thermal properties. The main advantage to this system is that it has a thermal transmissivity approximately 1/2 of that for single glazings. When a special coating is applied to one of the inside surfaces, this system can have a low shading coefficient as well. As can be seen from Tables 1 and 2, the double paned configuration probably has the best combination of SC, U and visible transmittance of all the materials evaluated. It is also the most expensive.

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SOLAR FILMS - These can be applied to either the interior or exterior surface of any existing window. Exterior applications are more thermally efficient, although this does create more bonding, weathering, and cleaning problems. These films are available in a number of colors and thicknesses, each with different solar and thermal properties. It should be noted that films can be designed with S.C. values of 0.10 or below, but these would be so dark and aesthetically displeasing as to destroy the original purpose of the window. Also, many metallic films have been known to be so reflective as to induce glare problems in surrounding buildings.

The film we tested, "3M Scotchtint Sun Control Film", had a shading coefficient comparable to the other materials evaluated. However, it had a substantially poorer visual transmittance, U value, and an apparently shorter useful life. Although this material is the cheapest and easiest to use for retro-fit operations, it may not be the most effective in the long run.

SPECIAL GLASSES - These can be manufactured with an even greater variety and styles than solar films. Unlike films, environmental degradation does not appear to be a problem. Glass panes with high absorbency sometimes do have problems with excessive thermal stresses and cracking though, unless special window frames are used. Special glasses are usually called for in the original design of the building and are not generally used for retrofit.

INTERNAL SHADES - These include roller shades, curtains, drapes, venetian blinds, etc. Internal shades are virtually never as efficient as other shading systems, because almost all the solar energy absorbed by them is convected directly

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into the room. They have advantages in that they are easy to install, have wide public acceptance, provide nighttime privacy, and can be modified (opened or closed) to suit the environmental conditions.

Numerous other configurations of shading systems exist, most of which can be put in one of the above classifications. A major exception would, of course, be a biologically controlled system. The proper placement of exterior plants can not only reduce solar heat gain, but also add an aesthetically appealing appearance to the window. Furthermore, transpiration of plants often creates a microclimate which is cooler than the surrounding ambient temperature, thereby reducing the inflow of heat due to thermal transference. An Additional advantage is that deciduous plants lose their foliage in the winter, allowing solar heating during the cooler parts of the year. In general, their use is practical only for residential and small commercial buildings.

Probably the most effective window strategy yet developed involves the use of an exterior shading screen along with a multiply glazed surface. Such a system has very low SC and U values (lower than each material alone), while still allowing good visual perception. However, this system tends to be very expensive.

There are a number of factors, other than the heat transfer properties of the shading material itself, that may be relevant in determining a materials' suitability for a given application. Below is a list of some of the more relevant considerations.

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LIGHTING - The effects of an increased dependency on artificial illumination after application of a shading system must be considered. The power supplied to most office buildings for illumination is around 10 to 30 watts/meter^2, depending on the task. This typically accounts for about 30% of a building's energy consumption. Direct solar radiation can have intensities around the 400 watts/meter^2 range, so it can significantly reduce this lighting load. However, radiation of this intensity can induce glare problems. Also many offices have fixed lighting systems that are either on or off. This type usually remains on, no matter what the solar lighting intensity is.

The human eye's sensitivity to light is a function of wavelength. Yellow-green light is generally considered to provide the greatest visibility per watt of light. Illumination that has a peak intensity in this range is the most visually efficient. Background diffuse solar radiation, consisting mostly of the shorter blue and green wavelengths diffracted by the earth's atmosphere has a peak wavelength close to that of yellow-green light. However, many people like the more conventional lighting which is stronger on the red end of the spectrum, because it helps bring out more vibrant flesh tones.

Lighting and aesthetics are closely related. The ability to be in visual contact with the outside world is one of the primary functions of a window. Any shading system which severely inhibits this function should not receive any further consideration.

CLEANING - Whenever any type of external sun screen is used, some provision should be made for window cleaning. These screens often collect a great deal of dust, and after a rain, much of it can get splashed onto the windows. Although the ensuing visual distortion is much less noticeable due to the shading effect of the screen, it can be

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quite distracting at low sun angles. This added maintenance expense should be considered along with the base price of these screens.

BUILDING CHARACTERISTICS - Placement of air conditioning ducts close to the window surface will tend to increase the amount of heat convected into the building. A building with a large thermal mass (i.e., lots of concrete or other dense, high specific heat material) will tend to absorb a great deal of the radiated heat and release it later at night. While in buildings with lots of carpet and paneling, this heat tends to show up much more quickly and causes a larger immediate drain on the air conditioning. In large buildings with a great deal of heat producing equipment, it may be desirable to reduce the solar heat gain as much as possible during all parts of the year, while in other buildings, it may be desirable to use some of this natural solar heating during some seasons. The building characteristics can be of comparable importance to the solar screen properties in the selection of a screening strategy.

VANDALISM - Exterior sun screens will tend to decrease the danger to building occupants from vandalism. However, louvered metal screens can easily be bent out of shape by rocks and other projectiles, while fiberglass screens tend to be more flexible and less subject to harm.

COST OF ENERGY - Generally, there is a greater demand for power during summer afternoons, and in the future, it may be priced accordingly. A screening strategy which admits mostly radiant heat (which can be absorbed into the building and exhausted later at night when energy costs might be lower) may therefore have a lower operating cost than

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one that admits mostly convective heat which puts an immediate load on the air conditioner system.

In addition, wind loading, ease of removal, infiltration, condensation and ventilation characteristics may be of importance in the screening materials selection.

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CONCLUSION

The effectiveness of a shading material to reduce the incoming sunlight can be determined easily by measuring the visible light transmittance. This property by itself, however, is not sufficient to ascertain the energy savings potential of the material.

Current state-of-the-art seems to indicate that no one shading system can be considered the most cost-effective in all situations. Interior temperature and air speed, window orientation, exposure, weather conditions, building latitude, time of day, time of year, and numerous other conditions all affect the relative utility of these materials. The complicated interactions between these factors are difficult to experimentally simulate or mathematically calculate with any degree of accuracy. Therefore, most discussions of these devices are inherently qualitative and lack rigorous scientific credibility. The Lawrence Berkeley Laboratory in Livermore, California, is currently involved in the evaluation of many screening materials, but their results may not be available until the 1980's.

It is generally recommended that a standard formalized testing procedure be adopted (such as an ASTM Standard) to evaluate window shading systems. This would clear up much of the obscurity and confusion regarding many of the solar manufacturer's claims. Also, a computer simulation program should be developed that would be able to model the overall effectiveness of a given system for a specific set of environmental conditions. Many subroutines already exist which could be used for its development.

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