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AN OUTDOOR EXPOSURE TESTING PROGRAM FOR OPTICAL MATERIALS USED IN SOLAR THERMAL ELECTRIC TECHNOLOGIES

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ABSTRACT

Developing low-cost, durable advanced optical materials is important for making solar thermal energy technologies viable for electricity production. The objectives of a new outdoor testing program recently initiated by the National Renewable Energy Laboratory (NREL) are to determine the expected lifetimes of candidate reflector materials and demonstrate their optical durability in real-world service conditions. NREL is working with both utilities and industry in a collaborative effort to achieve these objectives.

To date, simulated/accelerated exposure testing of these materials has not been correlated with actual outdoor exposure testing. Such a correlation is desirable to provide confidence in lifetime predictions based upon accelerated weathering results. This outdoor testing program will allow outdoor exposure data to be obtained for realistic environments and will establish a data base for correlating simulated/accelerated outdoor exposure data with actual outdoor exposure data.

In this program, candidate reflector materials are subjected to various outdoor exposure conditions in a network of sites across the southwestern United States. Important meteorological data are continuously recorded at these sites; these data will be analyzed for possible correlations with material optical performance. Weathered samples are characterized on a regular basis using a series of optical tests. These tests provide the basis for tracking material performance and durability with exposure time in the various outdoor environments.

This paper describes the outdoor testing program in more detail including meteorological monitoring capabilities and the optical tests that are performed on these materials.

INTRODUCTION

Efforts are presently underway to spur commercialization of solar thermal concentrator systems for electrical generation applications. For example, a major collaborative venture has been initiated between the U.S. Department of Energy (DOE), state and local public utilities, and private industry to convert the 10 MW Solar One pilot plant to Solar Two, an advanced molten salt central receiver design. A common element in all commercial solar thermal technologies is the need for optical reflector materials that are low cost, light weight, durable, and efficient (Stine, 1987). Consequently, it is important to demonstrate to potential investors and manufacturers the optical durability of candidate reflector materials in outdoor environments that are representative of prospective sites for solar system installation.

This paper describes work completed to date in developing an outdoor exposure network. One goal of this ongoing NREL solar electric research program is to establish and activate five outdoor exposure sites by March 1994 and possibly expand the program to additional sites over the next several years.

Solar concentrators represent a significant fraction of installed system cost, and reflector materials comprise a large portion of the costs associated with concentrators. The cost of existing reflector materials is regarded as too high by industrial concerns interested in manufacturing and marketing solar thermal systems. As a result, recent emphasis has been placed by industry on the development of lower-cost reflector materials. NREL is collaborating with various thin film industrial companies to develop advanced reflector materials having the potential for very low production cost. Because the optical durability of new candidate materials remains uncertain, the demonstration of their longevity during real-world exposure is critical to the reduction of perceived risks associated with this technology. A demonstration utilizing a complete outdoor exposure testing network can reduce risks and provide useful data for developing correlations between past, present, and future accelerated weathering data and real-world, real-time outdoor exposure data. This program is therefore considered to be an important element in solar, transportation and utility materials research and development (Carlsson, 1989; and Fischer, 1992).

The network will provide a diverse set of environmental conditions for materials exposure. To determine the most useful locations, a set of criteria was used to evaluate candidate sites. It was desirable to involve the utility industry and the solar power manufacturing industry to generate interest and support for solar thermal technologies and to identify sites deemed suitable for future solar thermal energy production. Thus, initial industry contacts were primarily directed at utilities and companies that already have shown interest in solar thermal technology as a possible renewable energy source. Initial exploratory contacts were made with members of the Solar Two Utility Consortium (Tyner, 1992). Each member contacted expressed an interest in assisting with this project. These members include Arizona Public Service (APS), Los Angeles Department of Water and Power, Sacramento Municipal Utility District (SMUD), Idaho Power, Utah Power, Southern California Edison, and Pacific Gas & Electric. In addition, Cummins Power Generation has expressed interest in using their Abilene, Texas facility as a test site. Cummins is actively developing Dish/Stirling technology for commercial markets. The information obtained from these contacts was used to select and implement five outdoor exposure test sites.

SITE SELECTION

A number of factors were considered in evaluating candidate outdoor exposure sites. Of primary interest was the level of support offered by the solar thermal industry and prospective utilities in assisting with the program. Such support included the identification and availability of utility or company owned property on which a test site might be located. In addition, it was considered desirable for the interested utility or company to assist with the installation and provide ongoing maintenance of the test site. This maintenance includes periodic inspection of the test site for damage, sample cleaning and regularly scheduled sample collections for optical measurements at NREL.

A second consideration was the desire for a certain amount of geographic diversity between sites so that samples would experience a variety of different weather conditions. Such diversity would also establish support for solar thermal electric technologies in general and outdoor testing in particular in different service territories.

The last major consideration was the availability of meteorological/atmospheric data. To understand the time-dependent environmental effects on optical materials, real-time meteorological and atmospheric data are needed. Some of this information may already be available either on-site or through a local monitoring network. Table 1 lists the meteorological/atmospheric quantities of interest. A good discussion of the various environmental stress factors is provided by Fischer (1992).

Very few if any existing meteorological/atmospheric networks have all the capabilities of interest. In particular, UV monitoring capabilities are very limited. Recent concerns with atmospheric ozone reduction have spurred an interest in more extensive UV monitoring (Gibson, 1991), but few existing stations have the necessary capabilities. This is of particular concern since UV radiation is an important contributor to the degradation of reflector materials in general (Schissel and Czanderna, 1980; and Masterson, 1983). Based on these facts, it was decided to install complete on-site meteorological data acquisition facilities. This would result in the greatest flexibility in data reduction and provide consistent and comparable data across the network. However, because atmospheric pollutant monitoring is so complex, costly and labor intensive, this capability was not included at the site. Instead, the availability of existing pollutant monitoring sites in proximity to the outdoor test site was a key factor in choosing sites. Thus, with the exception of pollutant monitoring, the availability of existing meteorological data networks was not a strong consideration.

As a result of these criteria, five sites have been selected. Three sites have been activated while the remaining two are in the process of being established. Active sites include the Rancho Seco Nuclear Generating Station owned by SMUD who is also providing support for this outdoor test site. Another is located at APS's Ocotillo STAR Center; it is supported by APS. A third site exists at NREL in Golden, CO. The fourth site will be located at Cummins Power Generation located in Abilene, TX. Cummins is supporting installation and operation of this site. A fifth site will likely be located at the Solar Two project near Barstow, CA.

OUTDOOR EXPOSURE TEST PLAN

The test plan for the outdoor exposure testing program has been chosen to conform as much as possible to ASTM Standards D 1435-85 and G 7-89 (ASTM, 1993; and ASTM, 1990). The meteorological quantities that will be recorded are solar radiation (both total spectrum and ultraviolet), temperature, precipitation, wind speed and direction, and relative humidity. Atmospheric pollutant data will be obtained through local National Environmental Protection Agency network stations or other stations in the immediate vicinity of each outdoor test site. More recent discussions on outdoor weathering as it pertains to these types of materials has led to special instrumentation for monitoring the higher energy UV-B radiation (Fischer, 1992). This band, between 300 and 320 nanometers, has been shown to contribute significantly to the degradation of certain polymer materials and therefore will

Table 1. List of Meteorological Quantities of Interest

Ultraviolet (UV) insolation (global)
Total solar insolation (global)
Temperature (ambient air, ground and sample rack backplane)
Relative humidity
Precipitation (rain, snow, ice)
Wind (speed and direction)
Atmospheric pollutants (Ozone, Sulfur, Chlorine and Nitrogen containing compounds)

be monitored independently of the total solar spectrum and broad band ultraviolet radiation.

The ASTM standards D 1435-85 and G 7-89 provide details on the actual exposure procedures. Exposure racks are used for mounting samples. These racks are installed facing due south and the racks are inclined to the latitude of the site. Samples are removed periodically and sent to NREL for optical measurements. Once characterized, the samples are returned to the test sites for additional exposure. The global hemispherical solar radiation measurements are recorded at the same inclination and orientation as the samples. This provides the best measure of incident radiation on the samples.

METEOROLOGICAL DATA ACQUISITION

A full complement of meteorological instrumentation and data acquisition hardware is installed at each of the three operational test sites. For monitoring total solar and broad band ultra-violet radiation, a Precision Spectral Pyranometer (PSP) and a Total Ultra-Violet Pyranometer (TUVR) are used. These instruments are manufactured by the Eppley Laboratories. For monitoring the UV-B portion of the spectrum, a unique UV-B pyranometer was selected for its radiometric response curve. Most UV-B instruments used in medical applications are designed with response curves which closely match the DNA action spectra of human skin. In general, the action spectra for materials tested in this project will be different and, in some cases, unknown, so a more symmetric and consistent response curve over the spectral band of interest is required. The UV-B pyranometer selected for this project, an EKO Model 210-W, has a Gaussian response curve over the UV-B band and is therefore a more appropriate choice for more general meteorological observations.

A wind monitor manufactured by R.M. Young is used to measure wind speed and direction. Air temperature and relative humidity are measured using a Rotronic MP-100 temperature/humidity probe. Ground temperature and sample rack back-plane temperature are measured using silicon integrated-circuit probes. Finally, daily precipitation is monitored using a Met-One heated rain gauge. Should the temperature fall below 5°C, the rain gauge is thermostatically controlled to melt snow or ice using a built-in heater.

With the exception of the wind speed sensor and the rain gauge, all of the sensors output an analog voltage signal. The rain gauge provides a digital accumulation signal. Each signal equates to a given column height of precipitation. The wind speed sensor outputs digital counts, where the number of counts per second is proportional to the wind speed. All of these signals, both analog and digital are fed into a Solus Systems, Inc. datalogger. The analog signal resolution is 10 bit, and signals can be sampled up to 87 times each second. The datalogger can store up to 21,000 samples. In addition to the real sensor inputs, the datalogger has eight virtual analog sensors and eight virtual digital sensors which retrieve data from memory address space instead of directly from the sensors. This allows the user to perform mathematical calculations on the real data (such as data averaging) and place the resultant values in these memory addresses for logging by the datalogger.

A 10 minute average of each measured quantity is employed. Sensors are polled every 10 seconds. This provides adequate response time for each sensor. A special calculation is used for wind speed and direction which conforms to what is known as the "wind rose." The 0-to-360° scale for wind direction is divided into four quadrants. When wind speed and direction samples are taken, the wind speed is added to whatever quadrant the wind direction lies. A counter keeps track of the number of wind direction occurrences within each quadrant. The resulting eight numbers (four sums and four counters) can be used to calculate average wind speed over the entire scale, or average wind speed within each quadrant. Histograms can be generated on a polar coordinate system, which results in the "wind rose" plot. This data is important in studying abrasion effects on materials caused by windborn particles impacting material surfaces.

The datalogger is programmed to continuously monitor sensors, maintain running averages, log data and download data to a host computer on a daily basis . Standard modem communications are used, and logic within the program assures that if data is lost during communication or communications are not established for any reason, the data remains in memory until a download is successfully completed. The datalogger's memory allows data to be stored for up to 6 days without a download. The host computer is set up at NREL and is dedicated to receiving incoming calls and subsequent data downloads from all the stations in the outdoor testing network. Software changes and enhancements can also be downloaded to the datalogger via the host computer. On-site operational problems, such as power or instrument failures, are handled with the help of the local personnel responsible for maintaining the site.

Meteorological stations associated with this project are fairly remote. A photograph of a completely intsalled outdoor testing site with sample racks and meteorological equipment is shown in Figure 1. The sensors and datalogger were chosen for ruggedness, reliability, self-operation and low maintenance. In addition, the datalogger software is easy to use and visually effective for monitoring in real-time.

MATERIAL CANDIDATES

A wide range of candidate reflector materials is being tested at the exposure sites. The various materials include glass/metal mirrors, metallized polymer reflectors, front surface reflectors, thin glass mirrors, and other advanced/innovative reflectors. Glass/metal samples provide benchmark standards to compare with the other candidates. State-of-the-art second surface silvered-polymer reflectors are also included.

NREL is collaborating with industrial partners to develop advanced reflector materials. These materials include front surface reflectors directly deposited on thin metal membrane substrate materials, an all-polymeric reflector concept, and an alternate second surface silvered-polymer reflector. A recent subcontracted survey of candidate alternative reflector materials (Business Factors, Inc., 1992) identified a silvered polyethylene terephthalate (PET, a thermoplastic co-polyester), with a protective hard coat deposited over the silver, as being attractive from both a technical and economic perspective.

Candidate reflector materials either suggested or provided by industry (both commercial and experimental products) or fabricated in-house at NREL will be subjected to accelerated weathering as a screening test (Schissel et al., 1991). Innovative materials that exhibit promising optical durability during accelerated weathering tests will be subjected to outdoor exposure testing as well.

Table 2 lists the reflector materials intended for outdoor testing. Others may be added as new materials are developed through ongoing research efforts. At present, the program is too

Figure 1. Photo of NREL Outdoor Test Site

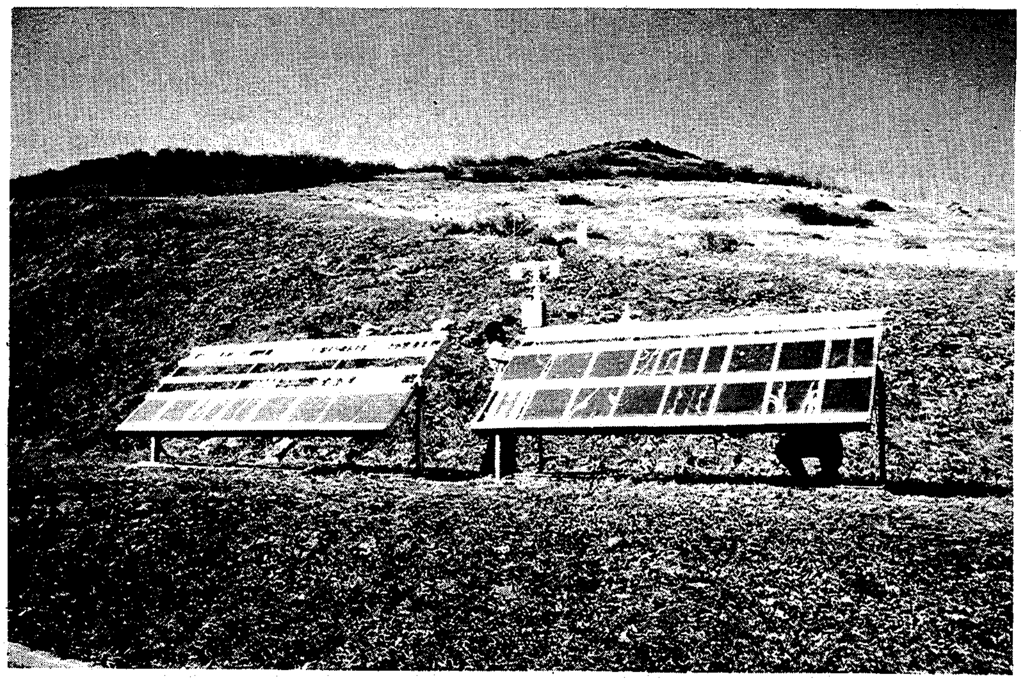

Table 2. Potential Candidate Reflector Materials.

Material	Company	Reflective Layer	Reflector Type[1]	Substrate Material[2]
Laminated Silvered glass	Advanced Thermal Systems (ATS)	Ag	2	Glass
Thin glass	Nagautuk Glass	Ag	2	Metal/Polymer
ECP-305	The 3M Co.	Ag	2	Al, PAl, SS
Silverlux (SS95)	3M	Ag	2	TBD[3]
Alumilux (SA85)	3M	Al	2	TBD
All-polymeric	Dow Chemical	Polymer	Interference	TBD
Silvered Teflon	Industrial Solar Technology (IST)	Ag	2	TBD
Metallized PET	Cummins Power Generation (CPG)	Al	1	PET
V1020	3M	Al	2	TBD

[1] Reflector Type: 1 = first surface, 2 = second surface
[2] Substrate Material: Al = Aluminum, PAl = painted Aluminum, SS = stainless steel
[3] TBD: to be determined

new for significant optical data to have been collected. Table 3 lists the sample sets which are currently under exposure testing at the three operating outdoor test sites.

Three to five replicates of each candidate material are exposed at each site. Sample size is roughly 2 inches by 2 inches. Larger samples may be included to investigate size dependent effects.

OPTICAL MEASUREMENT TEST PLAN

Candidate reflector materials are optically characterized prior to initiating exposure testing. Subsequently, samples are shipped back to NREL for remeasurement every 3 to 6 months and then returned to the field for further exposure. Two reflectance measurements are routinely used to monitor optical durability. Hemispherical reflectance is measured over the solar spectrum (250-2500 nm) using a dual-beam spectrometer equipped with an integrating sphere attachment. The spectral data is then used to calculate a solar-weighted hemispherical reflectance, which is indicative of the total amount of sunlight that is capable of being reflected.

Of particular interest is the specular reflectance of mirror materials. This quantity accounts for the portion of a reflected beam that reaches the receiver aperture and contributes to the collectable energy. A specular reflectometer is used to measure absolute specular reflectance as a function of collection angle at selected bandwidths (Susemihl and Schissel, 1987). Measurements are made over a range of full cone angles representative of those used in solar thermal electric concentrator applications.

REPORTING

A report detailing the latest outdoor exposure test data and results will be published annually and made available to industry and utilities. In addition, a paper describing the ongoing testing will be presented annually at relevant conferences, such as SOLTECH and/or the ASTM Accelerated and Outdoor Durability Testing Symposium. This will provide industry with ready access to the latest information on the progress of advanced reflector materials for solar thermal electric applications.

FUTURE WORK

Future efforts include activating the remaining test sites and any new sites which might be important (a location representative of a coastal environment is being considered). Also, the methodology for predicting reflective material service-life must be developed. This will include methods for correlating outdoor exposure data with accelerated exposure data. Once these tasks are completed, the program will continue to collect, analyze and correlate data for up to five years so that a complete and thorough data base can be established.

SUMMARY

The outdoor testing program outlined herein will provide useful data for understanding the real-world mechanisms that affect the durability and performance of solar thermal optical materials. The demonstration of the optical durability of candidate reflective materials at sites of interest to prospective utilities and industry will help spur investment and commercialization of solar thermal electric technologies.

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Table 3. Reflector Materials Currently Under Test.

Set #	Identification	APS	SMUD	NREL	Optical Measurements made at:
OET-1	ECP-305, SS95, SA85	X[1]	X	X	0, 3 months
OET-2	Nagautuk thin glass & ATS laminated glass mirrors	X	X	X	0 months
OET-3	ECP/Ag/Cu backed	X	X	X	0,3 months
OET-4	IST silvered FEP/Cu backed	X	X	X	0 months
OET-5	3M X09105/adhesive/Ag/ PET/adhesive	X	X	X	0 months
OET-6	3M X09105/adhesive/Ag/ PET/low tack adhesive	X	X	X	0 months

[1]X: currently under test at this site location

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