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**PRELIMINARY INVESTIGATION OF USER REQUIREMENTS
FOR SOLAR RADIATION DATA**

Final Report

**C. W. Hamilton
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October 29, 1976

**Battelle Columbus Laboratories
Columbus, Ohio**

**ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
Division of Solar Energy**

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A PRELIMINARY INVESTIGATION OF USER
REQUIREMENTS FOR SOLAR RADIATION DATA

to

ENVIRONMENTAL AND RESOURCE STUDIES BRANCH
SOLAR ENERGY DIVISION
ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

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INTRODUCTION AND SUMMARY

Individuals involved in emerging programs for the development of solar energy conversion technologies are creating a demand for more and better solar radiation data. The nature of this demand is generally aligned with the respective interests of the research and engineering communities. Specifically, the research community seeks improved measurement accuracy. It is claimed that high accuracy (perhaps up to a goal of 1 percent), is essential to attain a detailed understanding of radiation climatology. In contrast, the engineering community tends to accept current measurement accuracies (on the order of ± 10 percent) as being satisfactory. However, engineers identify as their primary need the expansion of the network of stations reporting total daily insolation plus more limited reporting of selected other measures. These latter measures include direct and scattered insolation on a horizontal surface, total radiation on tilted surfaces, spectral distribution of radiation, and long-wave radiation. (1,9)*

* Items in parentheses are references listed on page 47.

Assessment of the appropriateness of such demands for more and better solar radiation data is complicated by several factors. First, because the technologies for solar energy conversion are just emerging, engineering requirements for accuracy of solar radiation data cannot be reliably stated. Second, it is difficult to justify measurement goals involving very high accuracies given that climatological quantities are known to vary by several orders of magnitude.⁽⁴⁾ Third, needed rehabilitation of past data and lack of compression of massive amounts of climatological data into useful descriptive statistics, deters user determination of the utility of presently existing data. Fourth, and a consequence of the foregoing, it is not yet possible to assess the cost effectiveness of options for improving solar radiation data quality and/or expanding the data collection network. It is within this context that the purposes of the subject study were set. Specifically, it is the twofold intent of this study to

- (1) Make a preliminary assessment of the accuracy and precision of insolation data with respect to user requirements, and
- (2) Make a corresponding assessment of the minimum/maximum geographic network coverage.

In order to make these preliminary assessments, several specific questions have been addressed. Specifically:

- (1) How should users of solar radiation be classified and what principal uses of the data are made by each class?
- (2) What temporal and spatial properties of the data network are required to adequately serve the defined uses and users of solar radiation data?
- (3) To what degree does the existing network and associated data fulfill the desired data system properties?
- (4) What criteria should be applied in identifying and evaluating expanded network/data options.

The principal findings and conclusions of Battelle's investigation of these questions are summarized in the following paragraphs.

Summary

The principal conclusions of this preliminary investigation concerning classification of users and uses, requirements for solar radiation data accuracy, and network expansion are as follows:

- (1) Practical determinations of user requirements for radiation data should be responsive to varying technological, engineering, and application needs. A user/use segmentation of the solar energy community which effectively satisfies this criterion consists of classifying users by (a) collector type (as a surrogate for end-use application based on operating temperature) and (b) functional use of the data (site environmental characterizations, design, evaluation, and scientific investigation).
- (2) For general network planning, this user segmentation can be aggregated without essential loss of unique data needs. At this aggregated level, users of solar radiation data should be viewed as being of two types: forecasters and scientists. Forecasters include applications planners, manufacturers, and operators who use radiation data as input parameters in solving problems of siting, design, performance, reliability, etc. Scientists include atmospheric physicists and individuals of related disciplines who require simultaneously measured solar radiation and other geophysical data as inputs into detailed modeling studies of atmospheric and environmental interactions which attenuate and determine solar radiation received on the Earth's surface.^(3,4)
- (3) Within the collector type/functional data use classification, synthesis of judgments of solar energy technologists reveal that measurement accuracy and frequency of observations (integration times) increase with increasing collector concentration ratio. Similarly, accuracy and frequency requirements increase as functional data use proceeds from environmental suitability characterizations to scientific investigations. In contrast, geographic density of network coverage decreases with increasing concentration ratio and detail of investigation.
- (4) There is no convincing a priori evidence supporting general expansion of the routine network. This network presently consists of 35 NWS stations which measure and record solar radiation data required by forecasters.

Limited addition of stations to the routine network may be justified to the extent that some geographic regions having locally homogeneous climatological environments (coastal and mountain areas) are not now represented in the network. It follows that partitioning of the United States into a set of such climatologically homogeneous regions is a necessary first step.

- (5) The routine network should provide hourly and total daily measures of global, direct, and scattered radiation on a horizontal surface. Accuracy of radiation data recorded at routine network stations on the order of ± 5 percent should generally meet the requirements of forecasters. This objective appears to be a practical goal vis-a-vis a maximum achievable accuracy of ± 5 percent suggested by Machta and others.⁽⁴⁾ It should be noted that accuracy requirements depend on the characteristics of specific forecasting problems and vary from problem to problem. For example, forecasts of cumulative global radiation (e.g., monthly totals) will tend to be more precise than daily totals based on relatively imprecise measurements. In contrast, noncumulative forecasts (e.g., radiation for a given day) will be only as precise as the measurements on which it is based.
- (6) While improved instrumentation is desired, primary attention should be concentrated on procedures for uniform data quality assurance across all stations in the routine network. Effective decision making based on forecasts, involving temporal extrapolation and spatial interpolation, depend upon measurements of known accuracy at each station and on comparability of measurements across stations.
- (7) There appears to be general agreement in the scientific community that a research network consisting of five (5) to ten (10) stations is required. The purposes of this network will be to support research concerning fundamental geophysical laws associated with radiative transfer and long-term climatological trends. Observations made at these research stations should include diffuse radiation, measurement on tilted surface, spectral distribution of energy, moisture and aerosol content, albedo, etc. Accuracy requirements for the research network are very high; perhaps up to an order of magnitude better than those for the routine network.

These conclusions appear to represent a general consensus among solar energy technologists. However, quantitative benefit-cost analyses

warranting unconstrained investment in collecting more and better data are lacking. Accordingly, Battelle recommends a prudent "bootstrap" evolutionary approach in responding to perceived data requirements. This approach is aimed at simultaneously optimizing network expansion investments and forecasting procedures. Toward this end, Battelle recommends the following actions for network improvement:

(1) Routine Network

- Normal incidence pyrheliometers with mean solar time mounts should be added to all NWS routine network stations. In conjunction with the existing pyranometers, and with frequent adjustment to limit systematic errors (a) acceptable accuracy of direct and scattered insolation can be obtained, as well as (b) information for tilted surface insolation.
- Photometers should be added to a small number of existing routine network stations to measure turbidity and atmospheric water vapor content. Further extensions of the "turbidity sensing network" should be made only after the utility of the resultant data are clearly established.
- No new stations should be added to the routine network until their need is established based on network-forecasting method optimization studies. Possible exceptions to this network optimization recommendation might be addition of a few stations needed for support of large-scale demonstration programs or similar site-specific system applications.
- Observation frequency (integration times) of one hour for both direct and scattered insolation should serve most user needs.

(2) Research Network

- A research network with a station located in each of the macro-scale climatically homogeneous zones of the nation should receive near-term implementation priority. This network might include up to 10 stations.
- These stations should carry an instrument complement capable of generating data output recommended by Working Group on Instrumentation and Data Gathering as described on page 27 of this report. These requirements should be met using advanced designed pyranometers such as the PSP, active cavity pyrheliometers on true solar path mounts and commercially available photometers and photospectrometers.

- A primary use of research network data should consist of developing reliable forecasting techniques based on spatial interpolation and temporal extrapolation of routine network data. That is, it is one objective of the research network to minimize the need for future investment in major expansion of the routine network.

(3) Mobile Radiation Monitoring Units

- A small number of mobile units equipped with the same pyranometers and pyrhemliometers as those recommended for the routine network stations should be put into operation.
- These mobile units should be used to supplement routine network data for the purpose of micro-climate characterizations in urban areas, coastal zones, and areas of highly variable topography. In addition, these units can be used for verification studies of the practical limits of spatial interpolations of solar radiation characterizations.

Further, based on the foregoing conclusions and the preliminary analysis supporting them, Battelle concludes that the most pressing analytical need consists of determining the precision with which forecasts can be made for selected cumulative and noncumulative solar radiation cases. These cases should include problems of site-specific temporal extrapolation and between-site spatial interpolation. Accordingly, Battelle recommends that methods of alternative levels of sophistication be developed and applied to the following verifiable forecast problems:

- (1) Determine the expected accuracy and precision of annual forecasts based on extrapolation of the monthly insolation totals for the equinox months (March, September). This should be done using historical data of one year to "forecast" known results for the following year. If the accuracy and precision are acceptable, these results may indicate that mobile units could yield acceptable estimates of annual averages from samples taken during these two months of the year.
- (2) Suppose K stations are located within a climatically homogeneous region. Forecast the annual insolation totals for each of the K stations by interpolation of the historical data from the current year using the remaining (K-1) stations in the region. The procedure

should be repeated for each region. These forecasts would constitute relatively simple forecasting problems because no extrapolations to future times are required and no interpolations to locations without measurement stations are required.

- (3) Same as the preceding problem except that the forecasts would be made for future times at each station using past historical data at the remaining (K-1) stations.
- (4) Same as problem (2) except that the forecasts would be interpolated for selected locations that do not have measurement stations. Current data for the K stations would be used to generate the current year's "forecasts".
- (5) Same as problem (4) except that both interpolation among existing stations and extrapolation to "future" times would be used to generate the "forecasts".

The general objective of these problems consists of establishing, by numerical example, whether the existing network can provide forecasts that are sufficiently accurate and precise for engineering applications of solar energy. If no forecast deficiencies are found, then the existing network would be taken to be adequate. If forecast deficiencies are found, then it is expected that the kinds of deficiencies identified would indicate the kind of augmentation required for the existing network. That is, the number and location of additional stations required to yield adequate forecasts for engineering applications would be identified by the results obtained from these problems.

It is expected that the results of the recommended investigation will permit (a) matching of required sophistication of forecasting methods to the difficulty of the forecasting problem, (b) demonstration of the practical limits of precision of statistical forecasts as functions of solar radiation measurement accuracy and station spacing (within homogeneous climatic regions), (c) determination of station additions to the routine network and the consequent gains in forecasting precision, and (d) determination of minimum time periods for which radiation data should be recorded for purposes of making increasingly difficult forecasts.

CURRENT STATUS AND PROBLEMS IN
SOLAR RADIATION MONITORING

Eighty-six (86) weather stations in the United States measure and record solar radiation.⁽⁶⁾ Nineteen (19) National Weather Service (NWS) stations produce hourly and daily pyranometric measures of hemispheric solar radiation; 41 NWS stations and 26 cooperating stations produce daily measures only. Three (3) NWS and 2 cooperative stations record normal incidence measures using pyrheliometers. These measures are taken only at solar noon, at solar angles corresponding to air mass thicknesses of 2, 3, 4, and 5, and under clear weather conditions. Since 1950, the climatic and insolation measurements have been published monthly in the Climatological Data-National Summary, and are available on tape or punched cards from the National Climatic Center (NCC), Asheville, North Carolina. Most of the pyranometer stations have records of less than 20 years; only 7 stations have been in operation for over 30 years.⁽⁷⁾ Albuquerque, New Mexico, and Tucson, Arizona, are the only southwestern locations for which measured values of both total and normal incidence insolation are available.⁽⁸⁾ The only long-term (1947-1956) insolation measurements taken on nonhorizontal surfaces were taken at Blue Hill, Massachusetts.⁽⁹⁾ The NCC also publishes turbidity measurements taken with sunphotometers at 50 EPA-supported stations in the United States.⁽¹⁰⁾ A 15 percent decrease in direct insolation on clear days at Washington, D. C., between 1920 and 1970 is attributed to increased turbidity associated with industrialization.⁽¹¹⁾ Other studies indicate global radiation loss at ground level at 1 to 2 percent per 100 $\mu\text{g}/\text{m}^3$ atmospheric pollution concentration.⁽¹²⁾

Radiation climatology is plagued by a variety of problems. The most notable problem involves the Parson's black used with old-style Eppley pyranometers. After 1956, the black absorber gradually changed to a gray-green color on a large number of instruments. By 1966, the problem became serious, with reported errors of ± 5 percent to ± 30 percent. In September, 1972, the NWS requested the NCC to stop publishing these data. The rehabilitation of these data has been the subject of much discussion. As a result, several groups have recommended that these data be rehabilitated for all United States stations to an accuracy of at least 5 percent over a 10-year

period.⁽¹³⁾ The rehabilitation is in progress, but the publication for the corrected data is uncertain.⁽¹⁴⁾

Additional problems in radiation climatology include the following:

- (1) The Eppley normal incidence pyrheliometer has a view of approximately 6 degrees, whereas the sun intercepts an angle of approximately 1/2 degree. The measured radiation in the circumsolar field of view, particularly under hazy cirrus cloud conditions, can result in significant overestimation of normal incidence radiation.^(15,16)
- (2) The International Pyrheliometer Scale (IPS) is a relative, rather than absolute scale, and systematic errors of approximately - 2.2 percent have been associated with IPS measures.^(17,18)
- (3) The presence of UV radiation (0.3 to 0.4 μm) in the solar spectrum is of great significance because of the potential degradation of the optical properties of materials. However, except for limited measurements at a few sites (Washington, D. C.; Rockville, Maryland; Los Angeles, California) measured spectral variations for a variety of azimuth angles, altitudes, and atmospheric conditions are not available.⁽¹⁹⁾
- (4) Empirical procedures have been developed for converting insolation on tilted surfaces using monthly average daily total radiation on a horizontal surface. Because actual data are not available for nonhorizontal surfaces (excepting the vertical surfaces of Blue Hill) the accuracy of the procedures cannot be determined.⁽⁹⁾
- (5) The research community generally insists that improved measurement accuracy is essential to achieve the required understanding of radiation climatology. However, it is difficult to justify measurement goals of 1 percent accuracy for climatological quantities that are known to vary by several orders of magnitude, primarily because of highly variable cloud cover.⁽⁷⁾ The research community seeks to identify very small "signals" in the presence of large amounts of "noise". In contrast, the engineering community generally suggests that current accuracies are sufficient. The primary need is stated to be an expanded network of stations that report daily total insolation within ± 10 percent. These stations would be augmented by a few highly instrumental stations that measure total and diffuse insolation on a horizontal surface, together with total radiation on selected vertical and tilted surfaces.⁽⁹⁾

- (6) A large number of nontrivial problems are encountered in the processing of geophysical data. Such problems include the following:
 - (a) Large quantities of data exist, but often not at the sites of interest.
 - (b) Local variations in solar flux and related meteorological parameters, particularly in urban areas, coastal zones, and mountain regions, can severely limit the utility of applying data from a specific site (station) to the surrounding region as a whole.
 - (c) Severe interpolation problems result from intermittent data taken over short time intervals.
 - (d) Data are of questionable accuracy.
 - (e) Monthly totals are available when hourly measurements are wanted.
 - (f) Normal or UV insolation is wanted, but only total insolation is available.
 - (g) Nonhorizontal data wanted, but only horizontal data are available.
 - (h) "Typical" months or "typical" years are wanted, but must be painfully extracted from years of data.
 - (i) The simultaneous occurrence of selected variables are wanted (e.g., ambient temperature, relative humidity, wind speed, and insolation), but only time averages of individual variables are available, etc.
- (7) Reliable estimation of solar radiation at off-network station sites by means of spatial interpolation is made difficult because of anisotropic climatic variations in coastal and mountain regions. It has been shown that interpolated estimates derived from measurements at stations up to 500 km apart are reasonable within regions having uniform geophysical environments.⁽²⁰⁾ However, such uniformity (isotropic climatic variation) does not generally exist throughout the United States; and, in particular, in densely-populated urban areas which are targets for solar energy applications.
- (8) Methods for separating the direct from the diffuse components of global solar radiation are stated to be less than satisfactory.⁽⁴⁾ At the present time, only

five stations in the routine network provide pyrhelimeter measurements of direct irradiance. Because knowledge of direct irradiance is important to the design and development of several solar energy conversion systems, the weakness of existing methods constitutes a pressing problem. It is apparent that lacking improved methods the pyrhelimeter network will have to be greatly expanded.

The breadth of current problems in solar radiation monitoring exemplified above suggests that their resolution will require significant investment in development and deployment of improved instrumentation (especially pyrhelimeters) throughout an expanded network of stations. However, it is Battelle's tentative conclusion that such investments should be made incrementally in accord with simultaneous network/analytical modeling optimization approach cited in the recommendations section of this report. This conclusion derives mainly from the following reasons: First, advanced in modeling of climatological phenomena may constitute a viable alternative to long-term and generally more costly empirical data collection. For example, improved statistical models for reliably estimating global radiation based on sunshine (sky cover) would reduce the need for expansion of the routine network.⁽⁴⁾ Further, in the long term and at a higher level of modeling sophistication, use of radiative transfer theory incorporating cloud parameterization may yield both direct and diffuse radiation values. Second, user requirements for radiation data for evaluating system performance may be less demanding than has been assumed to be the case. For example, Balcomb and Hedstrom have developed a simplified method for sizing a solar collector array for space heating which calls for only monthly global radiation on a horizontal surface and heating degree days.⁽⁵⁾ As noted earlier in this report, relatively high precision in forecasts of monthly total radiation can be obtained even with inaccurate measurements because of the cumulative property of the forecast.

Based on the portrayal of the current status of solar radiation monitoring, the pertinent question is: should primary emphasis be directed toward expanded and improved data collection, or toward development of improved models of solar climatology? Attempting to answer this question exposes an essential dilemma. That is, too much emphasis on data collection

is both costly and unnecessary once adequate models are developed. But, in turn, adequate models cannot be developed in the absence of sufficient data. Thus, it is the proper balance between these two sides of the coin that is at the heart of formulating an appropriate strategy.

This argument follows from the simple fact that it is forecasts of future solar radiation environments that are required by the solar energy community, not historical records of the past. Accordingly, Battelle believes that the next steps in formulating appropriate needs for data quality and network size should consist of

- (1) Specifying a number of forecasting problems involving temporal extrapolation and spatial interpolation. These problems would include forecasts of both cumulative and noncumulative radiation values.
- (2) Development and verification of forecasting models matched to the difficulty of the respective problems.
- (3) Assessment of the utility of such forecasts in satisfying user needs.
- (4) Identification of requirements for data quantity and quality for the respective models.

ASSESSMENT OF USER REQUIREMENTS FOR SOLAR RADIATION DATA

Requirements for solar radiation data as reported in various workshop proceedings and other related literature generally constitute responses to those problems identified in the preceding section of this report. The principal thrust of these responses mainly consists of advancing the state of the art in solar climatology measurement science. Such advances include improvements in instrumentation design, increased frequency of calibration of in-service instruments to minimize systematic errors in data records, extension of the solar radiation monitoring network to provide both more dense geographic coverage and direct insolation measurement, as well as total insolation and establishment of several highly-instrumented stations to provide data for scientific investigations of atmospheric processes. The

specific aim of the foregoing is to provide a consistent and comprehensive solar radiation data base serving the needs of the most exacting user.

With this aim, and given the state of the art in radiation monitoring over the past decade, specific quantitative recommendations made to date may be summarized as follows:

- Total insolation data records generated at the NWS network stations over the last decade should be rehabilitated to an accuracy of 5 percent. Machta suggests a method based on using the ratio of expected solar radiation for a standard year to the observed radiation at true solar noon as a correction factor. Also, alternative linear interpolation techniques have been proposed by several participants in the 1973 Solar Energy Data Workshop.⁽²⁰⁾
- For future radiation monitoring, the routine network should record both total and direct insolation with accuracies (random error component), frequency and densities of geographic coverage as shown in Table 1.

TABLE 1. COMMON REQUIREMENTS FOR A SOLAR RADIATION DATA NETWORK

Instrumentation	Random Error			Frequency			Network	
	D	A	M	D	A	M	A	M
Pyranometer	1-2%	3%	5%	1 min.	10 min.	1 hr.	200 mi.	300 mi.
Pyrheliometer	1%	-	2%	1 min.	10 min.	1 hr.	300 mi.	-

D - Desirable, better than this is necessary

A - Acceptable, satisfies most applications

M - Mandatory, less than this is unsatisfactory.

Source: Conference of Solar Radiation Users, May 29-30, 1974.

These recommendations further include elimination of systematic errors through quality control and a pyrliometer scanning angle of less than 2 degrees.

- Five to ten research stations should be established to (a) determine correlations between routine network measurements and highly accurate corresponding measurements at the research stations (e.g., correlations between horizontal and tilted surface measurements) and (b) additional solar radiation parameters including spectral distribution, albedo, turbidity, IR (long-wave) radiation, etc.

It is evident that the goals contained in these recommendations represent reasonable advances in the current status of radiation measurement. Moreover, as noted earlier, the resultant data should adequately serve all but the most demanding needs (e.g., high concentration central receiver siting and system evaluation) of the user community. However, implementation of improvements in radiation monitoring entails significant financial investment - and, hence, investment decisions which should be based on suitable benefit-cost assessments. To properly make such assessments, it is necessary to examine data-requirement questions from the point of view of the practical needs of different users. It is from this point of view that users and uses are structured in the following paragraphs.

The approach adopted in structuring user data requirements is schematically displayed in Figure 1. The logic implied by structure shown in Figure 1 involves a four-step process.

- (1) End-use applications (e.g., space heating, food drying, generation of electric power) generally determine the type of solar energy conversion technology that is required.
- (2) The various energy conversion technologies (e.g., flat plate, concentrating collector, photovoltaic), in turn, define the solar flux and meteorological parameters which are determinants of system performance.
- (3) Uses of the solar flux and meteorological data (e.g., site suitability, engineering design, system evaluation) determine requirements for accuracy/precision, density of geographic coverage, and frequency of measurement.
- (4) These requirements finally must be translated into a practical network configuration.

The following subsections trace this process.

Relation of Energy Conversion Technologies to End-Use Applications

Solar energy thermal collector efficiency is a decreasing function of the temperature difference between the absorber and the ambient air

FIGURE 1. LOGIC STRUCTURE FOR IDENTIFYING USER REQUIREMENTS FOR SOLAR RADIATION AND METEOROLOGICAL DATA

surrounding the collector. More precisely, instantaneous efficiency is the energy/unit area removed by the transfer medium divided by the incident radiation. Figure 2 qualitatively depicts rates of change in efficiency for flat plate and concentrating collectors. It is seen that efficiency of flat plate collectors degrades sharply because of a high rate of heat loss from the absorber to the ambient air. Efficiency of concentrating collectors declines proportionately slower because the reduced size of the absorber relative to the collector aperture area. Because of this operating property, it is seen that effective temperature range increases as the collector concentration ratio increases.

Useful operating temperatures for 12 specific collector types are shown in Table 2. It can also be seen from the information given in Table 2 that to gain increasingly useful temperatures and operating efficiencies, system tracking requirements also become more demanding.

FIGURE 2. CHANGE IN SOLAR ENERGY COLLECTOR EFFICIENCY FOR FLAT PLATE AND CONCENTRATING COLLECTORS

TABLE 2. OPERATIONAL ATTRIBUTES OF VARIOUS TYPES OF SOLAR RADIATION COLLECTORS

Collector Type	Concentration Ratio	Useful Temperature, F	Tracking	Daily Efficiency, %	Radiation Input
Swimming Pool Heater	1	100-125	No	20-30	Direct and scattered
Shallow Pond	1	100-150	No	30-40	Ditto
Flat Plate/Air	1	125-175	No	25-40	"
Flat Plate/Liquid	1	125-200	No	30-45	"
Evacuated Tubular	1-2	150-300	No	50-60	Direct and most scattered
V-Type Collector	1.5-2	150-200	Seasonal	40-50	Direct and some scattered
Compound Parabolic	2-8	200-350	Ditto	45-55	Ditto
Fresnel Concentrator	50-1000	300-700	Diurnal/ one-axis	40-55	Direct
Parabolic Cylinder	20-100	300-800	Ditto	55-65	Direct
Circular Cylinder	20-60	300-600	"	45-60	Direct
Paraboloid	1000-5000	800-2000	Diurnal/ two-axis	50-65	Direct
Central Receiver	1000-10,000	1000-3000	Ditto	60-70	Direct

Given that end uses can be usefully defined in terms of their respective temperature generation requirements, the relationships described above lead to a natural classification of solar energy applications. That is, end-use application implies a required operating temperature which, in turn, is in approximate one-one correspondence with the geometries of identifiable solar collector types. Such a classification has been previously reported by Hoffman and Rapp.⁽²¹⁾ Table 3, adapted from their work, shows representative end-use applications, their approximate temperature ranges, and the correspondingly applicable collector types.

TABLE 3. COLLECTOR TYPES AND CORRESPONDING APPLICATIONS

Collector Type	Approximate Temperature Range, F	Representative Applications
Flat plate	100-200	Aqua-culture Swimming pool heating Fermentation Some greenhouse use Space heating Some food drying Space cooling
Low concentration	150-300	Space cooling Food drying Water distillation Some process heat
Medium concentration	300-600	Process heat
High concentration	700-5,000	Electrical energy production solar furnace
Photovoltaic	*	Electrical energy production

This end-use temperature-collector-type classification represents one dimension of a two-dimensional categorization of users/uses. The second dimension adopted in further defining needs consists of the purposes for which the data are required. Toward this end, five data use purposes are characterized in the following paragraphs.

* In surface temperatures for concentrating photovoltaic systems should be less than 300 F to prevent severe degradation. For high concentration ratios (30-40), forced convection is required to cool photovoltaic cells to this level.

Uses of Solar Radiation and Meteorological Data

Solar radiation and related meteorological data serve five generic purposes in development and deployment of solar energy conversion systems.*

- (1) Determinations of geographic environmental suitability
- (2) Empirical based design specifications for collector materials, components, and system configurations
- (3) Evaluation of collector performance
- (4) Routine in-service energy conversion system operational control
- (5) Scientific investigations.

Each of these uses imply varying technology-specific requirements in parameters to be measured on data accuracy/precision, geographic coverage, frequency of observation, and duration of the data-collection period.

Environmental Suitability

Determinations of environmental suitability for various solar energy conversion systems range from geographically widespread climatic surveys for flat plate and low concentration collector applications (space heating, cooling, water heating, some agricultural and biomass uses) to optimum site location searches for high concentration collector or photovoltaic applications (generation of electric power). Thus, for widespread solar technology applications, dense geographic data coverage is important. However, measurement precision (assuming minimization of systematic errors through suitable quality control) and frequency of measurement are of secondary importance. This lesser importance stems from (a) the presumption that end-use applications in widely varying climatic environments will involve generally common engineering designs differing mainly in collector area and storage system capacity and (2) the property that systems used in such applications have relatively high thermal inertia and, hence, are not sensitive to short-term (less than an hour) variations in solar flux.

* This data purpose classification closely parallels that adopted by Machta in his analysis of requirements for monitoring solar radiation. (4)

In contrast, determinations of environmental suitability for high concentration ratio systems call for virtually opposite priorities in data requirements. That is, in this instance, one requires accurate, continuous recording of the direct component of solar flux, but for relatively few site-specific locations. The determining property for high concentration ratio systems is insolation operating threshold. In particular, performance of such systems is very sensitive to transients caused by rapid gradients in solar flux. Partly cloudy days constitute a representative example of such an environmental condition. As illustrated in Figure 3, hourly-integrated measurements of direct solar flux could fail to reveal short-term transients. In this example, transient effects to midday solar flux gradients would effectively shut down a high ratio concentrating collector--a performance outcome not predictable from hourly-integrated solar flux values. Such gross differences in data needs as suggested by the foregoing are indicative of the difficulty in reaching compromises for network data collection which are universally acceptable.

FIGURE 3. ILLUSTRATION OF MIDDAY SCATTERED CLOUDS CONCEALED BY HOURLY-INTEGRATED SOLAR FLUX VALUES

Engineering Design

A frequently used approach for preliminary design purposes consists of seeking collector designs which maximize useful energy gain given "average" steady-state environmental conditions. Such steady-state conditions typically are expressed in terms of average daily, monthly, seasonal, or yearly solar intensity inputs. Recent concern in the radiation measurement community for a commonly agreed upon definition of a "standard year" stems from this design approach. However, more detailed collector design must be based on performance tradeoffs over the range of temporal and spatial variations in solar intensity input expected to occur in end-use applications. Results of performance tradeoff estimates shape decisions on materials, components, collector and storage capacity, installation and operational control. Thus, in sum, engineering design requires solar radiation and meteorological data for the following:

- Characterizing the parametric range of environmental exposure of given systems, the duration of exposure to various environmental conditions, and the frequency of their occurrence
- Selecting materials (e.g., specially selective coatings, heat transfer media, encapsulating materials), component design (e.g., collector size, storage capacity), and operational control (e.g., collector tilt angle, tracking systems).

Superimposed on the above is economic evaluation of system performance in their planned applications.

The first data use--characterization of the environments in which end-use applications are anticipated--demands measurement over a fairly dense geographic network and data records of at least five years and preferably ten-years duration.* Requirements for accuracy are generally moderate depending on the collector type (and, hence, end-use application). Liu suggests that for flat-plate collectors, an accuracy of 10 percent in total integrated

* There is historic evidence that weather patterns vary over cycles of 10, 30, and 90-years duration. It seems reasonable that data records used for application design purposes should span the short (10-year) weather cycle.

daily isolation is acceptable.⁽²²⁾ Given natural variability in order of magnitude ranges at given sites, as well as between sites, even lower accuracy (assuming concern for random error only) is probably acceptable.

Design studies for concentrating and photovoltaic systems generally require data of higher accuracy/precision than for flat-plate collectors; but, on the other hand, require less dense geographic coverage. For high concentration ratio systems, Vant-Hull and Hildebrand cite the need for direct beam solar intensity as a function of the angle from the center of the sun with 0.1 degree resolution over a 2 to 5 degree half angle.⁽¹⁶⁾ These data, in conjunction with distributions of haze density and turbidity measurement, would facilitate preparation of reliable direct insolation contour maps for purposes of site selection and optimization of receiver size and configuration. To obtain such measurements the existing radiation network would have to be supplemented with sun photometers and variable aperture pyrheliometers. The cost effectiveness of such a course of action is difficult to assess because the error in current direct beam measurement attributable to circumsolar effects (and, hence, the value of more precise data) is not known. In this regard, Peterson hypothesizes that circumsolar haze having a brightness equal to one percent of that of the solar disc would approximately double the direct beam insolation recorded by currently used 5.7 degree aperture pyrheliometers. Thus, while it is apparent that high angular resolution direct beam insolation data are needed for high concentration ratio system design, it seems prudent to require such measurement only at research network monitoring stations at the present time.

In summary, it is seen that data requirements for use in design studies must account for natural (environmental) variability in solar intensity. Because natural variability in virtually all environmental parameters effecting collector performance is large, high measurement accuracy does not appear to be essential. This general conclusion, however, does not apply uniformly across design needs for different collector types. Specifically, as suggested by the above examples, widespread application of flat plate and mildly concentrating collectors generate a demand for geographically dense, but relatively low accuracy data. Highly concentrating collectors, in contrast will be installed at geographically selective sites where it is forecast

that solar intensity will (a) exceed receiver operating threshold for long time periods and (b) not be subject to frequent short-term (minute-to-minute) fluctuations. In this instance, data of relatively high accuracy (with averaging times for pyrliometer data on the order of 10 minutes) is needed; but, at fewer locations judged a priori, to be candidate sites for such systems. The implied rule of thumb is that required design data accuracy is an increasing function of concentration ratio, and that geographic coverage is a decreasing function of concentration ratio. Finally, for design analysis of all collector types, at least ten and preferably twenty-year environmental forecasts are required.

Performance Evaluation

The purposes of performance evaluation tests are two-fold: (a) to measure actual collector performance against predicted performance for given designs (i.e., how well does the collector meet design objectives?), and (b) to compare observed performances of competing collector types and/or designs of the same collector type. Additionally, of course, the results of such tests constitute feedback data for design improvement. The dominant requirement for environmental data in these instances is that relevant solar intensity input parameters incident on the collector be precisely known. This need for high precision stems from the fact that observed differences in collector performance can be attributed to design properties only if the magnitudes of such differences are large relative to the error variance in measured solar intensity input. Specifically, the root mean square error (RMS) associated with an estimate of collector efficiency is given by: (23)

$$\frac{\sigma_{\eta}}{\eta} = \left[\frac{\sigma_{\dot{m}}^2}{\dot{m}^2} + \frac{\sigma_{c_{t,f}}^2}{c_{t,f}^2} + \frac{\sigma_{\Delta t}^2}{\Delta t^2} + \frac{\sigma_I^2}{I^2} \right]^{1/2},$$

where η = collector efficiency

$\dot{m}$ = mass flow rate of the transfer fluid

$c_{t,f}$ = specific heat of the transfer fluid

Δt = temperature difference between the average absorber temperature and the ambient air temperature, and

I = insolation incident on the collector surface.

It is the general consensus among solar energy researchers that the first three components of variation in the above equation yield a collective RMS error in estimated efficiency on the order of one per cent. However, the error associated with estimated insolation incident on the collector surface is about five percent at the present state-of-the-art. The combined result of these variance components (shown in Figure 4) is that the RMS error in estimated collector efficiency is essentially equal to the RMS error in measured insolation incident on the collector.

The implication of the level of uncertainty for engineering evaluations of collector efficiency are illustrated by the following examples. Suppose all measurement errors except insolation are negligible, and the insolation RMS error is five percent for a quasi-stationary 15 minute collector test. Then, for a single collector test a difference between observed efficiency and theoretically predicted efficiency of less than about 10 percent would not be interpreted as being statistically significant. Analogously, in a comparative test of two collector designs, an observed difference on the order of 14 percent would be required to conclude with high confidence that one collector design is superior to the second. To view such error variance magnitudes in perspective, various collector design studies suggests average efficiency differences of 5-10 percent for various mildly concentrating collectors (evacuated tubular, V-type, CPC, Fresnel), 10-20 percent for one or two cover flat plate collectors, and about 5 percent for various spectrally or non-spectrally selective absorber coatings. Thus, it is apparent that the current insolation measurement precision is at best marginally sufficient for collector evaluation purposes.

The sources of error in the measurement of insolation are of two types. The first stems from the natural time dependent variability of the directional distribution of spectral irradiance to which the collector is exposed. Contributions to the error variance in this instance stem from variable collector response to radiation at high incidence angles (greater than 40°), absorption and scattering due to increasing air mass thickness and the ratio of direct to scattered radiation. These are significant sources of error, but should not be overstated. In particular, useful power output is generated from solar flux collected at incidence angles less than 40° from

FIGURE 4. UNCERTAINTY IN SOLAR COLLECTOR THERMAL EFFICIENCY AS A FUNCTION OF THE UNCERTAINTY IN INSOLATION⁽²³⁾

the normal of the collector. Thus, low weighting is given to the larger error sources associated with high-incidence angle measurements.

The second type of error source is associated with instrument properties. Specifically, this error source includes instrument alignment, stability of calibration, ambient temperature-dependent response characteristics, and nonlinear response characteristics. Alignment is an especially important problem in performance evaluation of collectors tilted at some angle to the horizontal. Apart from alignment, these instrument-related factors currently lead to an RMS error of 2 to 3 percent.

In summary, collector evaluation requires an accuracy in insolation measurement which strains the present state of the art. To some extent, required improvements will be gained through reduction of systematic errors associated with instrument properties. Errors associated with variability in the directional distribution of radiation will generally have to be compensated for through test replications. Performance evaluations, however, are collector site-specific and, hence, impose no general network requirements. This latter point raises a caution for ensuring comparability of test results at different times and sites based on instruments which may not be calibrated against common standards.

Scientific Investigations

Scientific investigation comprises two general categories of activity, each of which is directly linked to the practical application purposes described in preceding paragraphs. The first category consists of investigations aimed at understanding how atmospheric and environmental processes attenuate solar radiation received at the surface of the earth. The results of such investigations can be used to better interpret simpler and less precise measurements made at routine network stations. That is, atmospheric model calculations can be substituted for extensive empirical data collection in characterizing the attenuation of solar flux at routine network stations. The second category of scientific investigations consists of identifying long-range trends in solar climatology. Such information is of direct use in

making environmental forecasts over future time periods commensurate with expected energy conversion system life cycles.

For both purposes, highly accurate and simultaneous measurements of many solar flux and meteorological variables is required. Specifically, the Working Group on Instrumentation and Data Gathering cites the following research network measurement requirements⁽²¹⁾:

- the energy falling on flat surfaces with arbitrary orientation to the vertical and the points of the compass.
- direct and/or diffuse radiation by spectral bands scanning over the sky with an angular resolution around the sun of 0.1° up to an acceptance angle of the routine network's direct solar radiation sensor (now 6°) then about 10° for the rest of the sky. The spectral resolution should be between 100 and 500 Å.
- long wave radiation including conversion of the results to an effective sky temperature or other form needed to measure outgoing longwave radiation.
- the typical albedo at and surrounding each station under varying states of terrain (snow, summer, winter, etc.) by aircraft or satellite.
- conventional weather elements such as temperature, pressure, humidity, wind, and cloud cover plus selected special measurements such as wind gustiness, total precipitable water, and total ozone.
- spectral resolution to at least 1Å and sky polarization at one of the research stations.

Additionally for correlation analyses, measurement of total, direct and diffuse insolation, percent sunshine, and turbidity should be made with the same instrumentation and quality control procedures as at the routine network stations.

Network Monitoring Requirements

It is evident from the discussion in the preceding section that user requirements for solar flux and meteorological data vary widely depending on the type of collector considered and on the intended functional use of the data. The nature of these varying data requirements is illustrated in Tables 4, 5, and 6. Table 4 summarizes the relative importance of selected parameter measurements for flat plate, concentrating collector, and photovoltaic systems. This assessment of relative importance encompasses the following data-use considerations:

- Geographically dense observation of percent sunshine and/or cloud cover can be used to calculate estimates of total insolation (and possibly direct and scattered insolation based on cloud cover parameterization) where accuracy requirements are not high. Papers by Machta and Randall outline both regression analyses and radiation transfer theory approaches for this purpose. (4,24) Moreover, through correlations with observations of direct and scattered insolations at the routine NWS network stations, more reliable spatial interpolations of solar flux can be made within climatically homogeneous regions. The practical utility of such data is effectively illustrated by the cloud cover variability in insolation as shown in Figure 5.
- Both direct and scattered insolation measurements are universally required. Although of secondary importance (when total insolation is 20 to 30 percent below design value), variations in the ratio of direct to scattered insolation influence flat-plate collector size determinations. (25) The wide variation and, hence, an indication of the need to record the ratio of direct to scattered insolation is a function of zenith angle, and urban and desert climate is illustrated in Figure 6. This figure shows, for example, that scattered insolation is about 27 percent of total insolation in urban environments. The ratio of direct to scattered insolation, of course, varies significantly among urban areas because of both natural microclimatological and pollution-induced attenuation properties.
- Spectral data are primarily required for research purposes in determinations of appropriate spectrally-selective absorber coatings, UV degradation effects on photovoltaic materials and the effects of atmospheric pollutants on

TABLE 4. RELATIVE IMPORTANCE OF SOLAR FLUX AND METEOROLOGICAL MEASUREMENT AS A FUNCTION OF COLLECTOR TYPE

	Flat Plate	Low Concentration	Medium Concentration	High Concentration	Photo- voltaic
Sunshine	P	P	--	--	--
Cloud cover	P	P	--	--	--
Total radiation	P	--	--	--	P
Direct radiation	S	P	P	P	P (a)
Scattered radiation	S	S (b)	--	--	--
Spectral distribution	S (c)	S (c)	--	--	P
Turbidity	S	P	P	P	P
Dry bulb temperature	S	P	P	P	P
Dew point temperature	S	--	--	--	--
Wind speed and direction	S	P	P	P	P
Precipitation	P	P	P	P	P

(a) Direct radiation data needed for concentrating photovoltaic applications.

(b) As shown in Table 2, low concentration collectors will absorb some scattered radiation.

(c) Spectral data needed for some biomass applications.

P = primary measurements.

S = secondary measurements.

TABLE 5. GENERAL PORTRAYAL OF STRINGENCY OF SOLAR RADIATION DATA REQUIREMENTS AS A FUNCTION OF COLLECTOR TYPE (SURROGATE FOR END-USE APPLICATION) AND DATA USE PURPOSE

Data Use	Collector Type				
	Flat Plate	Low Concentration	Medium Concentration	High Concentration	Photo-voltaic
Geographic environmental suitability	Measurement accuracy →				
Engineering design	Measurement frequency →				
Performance evaluation	Density of geographic coverage ←				
Short-term operational control	Arrow indicates direction of increasingly demanding data needs				
Scientific investigation					

TABLE 6. MEASUREMENT REQUIREMENTS FOR ACCURACY, FREQUENCY, AND DENSITY OF GEOGRAPHIC COVERAGE BASED ON COLLECTOR TYPE AND DATA USE CATEGORY

Data Use	Data Requirements	Collector Type				
		Flat Plate	Low Concentration	Medium Concentration	High Concentration	Photovoltaic
Geographic environmental suitability	Accuracy Frequency Coverage	Low Monthly Dense	Low Monthly Dense	Moderate Daily Moderately dense	High ~Hourly Limited	High ~Hourly Limited
Engineering design	Accuracy Frequency Coverage	Moderate Daily Moderately dense	Moderate Daily Moderately dense	Moderate Daily Moderately dense	High ~Hourly Limited	High Hourly Limited
Performance evaluation	Accuracy Frequency Coverage	High Hourly NA	High Hourly NA	High ~Hourly NA	High ~Continuous NA	High ~Hourly NA
Short-term operational control	Accuracy Frequency Coverage	Moderate Daily Dense	Moderate Daily Dense	High Hourly Site-specific	High ~Continuous Site-specific	High ~Continuous Site-specific
Scientific investigations	Accuracy Frequency Coverage	<div> <div>←</div> <div>High ~Continuous Very limited</div> <div>→</div> </div>

FIGURE 5. GROUND LEVEL SOLAR FLUX FOR VARIOUS CLOUD CONDITIONS
 (Source: NBS Technical Note 899, Development of
 Proposed Standards for Testing Solar Collectors and
 Thermal Storage Devices) (23)

FIGURE 6. REPRESENTATIVE DISTRIBUTIONS OF DIRECT AND SCATTERED SOLAR FLUX FOR URBAN AND DESERT ENVIRONMENTS (ADAPTED FROM MEINEL & MEINEL) (26)

solar flux attenuation. Spectrally-selective coatings improve collector optical efficiency through increased absorptance while simultaneously holding emittance to acceptably low levels. Masterson describes several techniques for extending selective surface technology to high-temperature (500 C) applications (medium and high concentration ratio collectors).⁽²⁷⁾ It is generally known that exposure to photovoltaic cells to wavelengths in the near UV causes serious degradation. However, lacking comprehensive degradation data on photovoltaic cells in well-instrumented UV exposure tests, it is difficult to assess impacts on life-cycle operation.

- Measurement of standard meteorological variables (temperature, wind speed and direction, precipitation) are required on the same time scale as solar flux measurements. Useful environmental forecasts for all solar energy applications require knowledge of the frequency and duration of combinations of these variables.

Table 5 qualitatively portrays the measurement requirements for the solar flux parameters discussed in the preceding paragraph. It is seen from this table that accuracy and measurement frequency requirements increase with increasing collector concentration ratio; and also increase with increasing detail of collector and/or site analyses. These requirements are offset, however, for density of geographic coverage which decreases with increasing collector concentration ratio and analysis detail. At this time, these requirements should be judged principally as indicators of relative needs as functions of collector type and data use. Determinations of absolute measurement requirements are clouded by several uncertainties. First, technologies entailed in solar energy conversion systems constitute rapidly moving targets. Measurement requirements stem more from technical capabilities in instrumentation and theoretical calculations of system response characteristics than from empirical investigations. In this situation, data requirements tend to be overstated to ensure that whatever data may be needed will be available. Given that 10-year (or longer) data records are required for environmental forecasting purposes, this "safety factor" position cannot be dismissed lightly. Clearly, the opportunity cost of acting in accord with understated needs is high. Second, extensive environmental forecasts of solar climatology have not been made. Such forecasts will involve development of various

techniques for spatial interpolation, temporal extrapolation and correlation of solar flux and meteorological parameters. The results of such forecasting efforts should provide a currently nonexistent quantitative foundation for decisions on network data monitoring. Specific types of forecasting problems that should be treated are described in the following section of this report. Third, and essentially a consequence of the foregoing, it is difficult to quantify the tradeoffs between the benefits and costs of improved data monitoring. Studies which have been made of automated station operations, however, suggest that total monitoring costs per station are relatively insensitive to instrument costs. (28,29) The implication of this finding is that high-measurement accuracy and frequency (within the state of the art) can be obtained at modest cost. The dominant cost component, of course, is associated with the number of monitoring stations required to provide acceptable density of geographic coverage.

Network Configuration

It is apparent from the preceding description of radiation monitoring needs that a permanent network of stations which would provide all measurements desired by the solar energy technologist at the desired times and places is impractical. Put alternatively, the probable cost of implementing a monitoring network designed to "highest use" demands cannot be quantitatively justified in terms of user benefits. Thus, it follows that a specific rationale must be specified in terms of which the monitoring network (including number and location of monitoring stations, and sophistication of instrumentation) would be expanded only to the extent that such expansion can be shown to be cost effective. This rationale should include the following criteria (and means for making acceptable tradeoffs among them):

- Estimated user benefits with respect to energy conversion system design, development and deployment (demonstration and commercialization). These user benefits should be segmented by collector type as a surrogate for end-use applications. Benefits to the design and development process generally refer to effective technological progression and entail data-dependent decisions on materials,

components, and optimum system configuration. Deployment benefits generally refer to proper siting decisions, system size determinations, and interfaces with conventional energy supply systems.

- Station capital and operating costs including capabilities of currently available monitoring instruments, investment needs for given advances in instrument capability, and costs of other supporting equipment (precision tracking mounts, recorders, integrators, etc.)
- Network configuration options and costs over time including routine and research stations, mobile units, satellite monitoring, and associated data management systems for reporting descriptive statistics and forecasts.

At this time, user benefits (value of information for those activities cited in the first criterion) are, at best, qualitatively known. In this regard, the relative importance statements for accuracy, frequency, and density summarized in Table 6 represent generally perceived needs, but lack quantitative calculations of actual utility. Instrument capabilities and costs--the second criterion--are best known. High-quality pyranometers (cosine response, temperature compensation, and nonlinearity combined RMS error of 2 to 3 percent) are commercially available for approximately \$1,000. Normal incidence pyrhemometers are available for about the same cost, and highly accurate active cavity pyrhemometers cost on the order of \$3,800.⁽²²⁾ The larger expense items are station maintenance and servicing (25 to 33 percent of initial capitalization) and data processing (\$1,000/parameter/year/station for hourly data).⁽¹⁴⁾ Determinations of the cost effectiveness of possible network configurations are currently lacking. In Battelle's judgment, such determinations depend on the quality of national and regional solar climate statistical descriptions and forecasts which can be obtained using spatial interpolation and temporal extrapolation techniques.

Given the current state of limited knowledge on the user benefits and costs of more and better radiation data, it is prudent to proceed slowly. At the same time, it is recognized that reliable data records spanning at least 10 years will be required; hence, postponement of implementation actions until definitive benefit cost analyses are made is appropriate. Accordingly, recommendations for monitoring network actions are given below

which constitute a "bootstrap" evolution for increasing capability. That is, a balance is sought between strong emphasis on costly data collection through a greatly expanded routine network and development of models which could later supplant the need for widespread data collection. Within this context, Battelle's overall recommendations are as follows:

- To upgrade data quantity and quality at existing NWS routine network stations through addition of pyrheliometers and to lesser extent, photometers. Also, rigorous quality control should be maintained.
- To implement a limited research network for purposes of model development aimed at enhancing site characterization and forecasts.

Specific recommendations are as follows:

(1) Routine Network

- Normal incidence pyrheliometers with mean solar time mounts should be added to all NWS routine network stations. In conjunction with the existing pyranometers, and with frequent adjustment to limit systematic errors (a) acceptable accuracy of direct and scattered insolation can be obtained, as well as (b) information for tilted surface insolation.
- Photometers should be added to a small number of existing routine network stations to measure turbidity and atmospheric water vapor content. Further extensions of the "turbidity sensing network" should be made only after the utility of the resultant data is clearly established.
- No new stations should be added to the routine network until their need is established based on network-forecasting method optimization studies. Possible exceptions to this network optimization recommendation might be addition of a few stations needed for support of large-scale demonstration programs or similar site-specific system applications.
- Observation frequency (integration times) of one hour for both direct and scattered insolation should serve most user needs.

(2) Research Network

- A research network with a station located in each of the macro-scale climatically homogeneous zones of the nation should receive near-term implementation priority. This network might include up to 10 stations.

- These stations should carry an instrument complement capable of generating data output recommended by Working Group on Instrumentation and Data Gathering as described on page 27 of this report. These requirements should be met using advanced designed pyranometers such as the PSP, active cavity pyrhemliometers on true solar path mounts and commercially available photometers and photospectrometers.
- A primary use of research network data should consist of developing reliable forecasting techniques based on spatial interpolation and temperal extrapolation of routine network data. That is, it is one objective of the research network to minimize the need for tuture investment in major expansion of the routine network.

(3) Mobile Radiation Monitoring Units

- A small number of mobile units equipped with the same pyranometers and pyrhemliometers as those recommended for the routine network stations should be put into operation.
- These mobile units should be used to supplement routine network data for the purpose of micro-climate characterizations in urban areas, coastal zones, and areas of highly variable topography. In addition, these units can be used for verification studies of the practical limits of spatial interpolations of solar radiation characterizations.

DEVELOPMENT OF METHODS FOR GENERATING FORECASTS
OF FUTURE SOLAR CLIMATOLOGY

As described earlier in this report, the major decision problem in solar resource assessment consists of the dual optimization of network (data) expansion and concomitant forecasting procedures. In this section, an approach is described for treating the forecasting side of this overall problem. Battelle believes that implementation of the proposed forecasting approach in conjunction with the previously stated network expansion recommendations will maximize the cost effectiveness of solar resource assessment with respect to user needs. For purposes of characterizing the following forecasting approach, a more aggregated classification of users is sufficient.

This class consists of two user categories: forecasters and scientists. Battelle views the users of solar radiation data from the routine network as forecasters; the users of the data from the research network are scientists. The user of the routine network is assumed to be primarily interested in the data as input parameters to problems of design, reliability, performance, etc. of solar-based systems. The user of the research network is primarily interested in obtaining a better understanding of the physical and biological laws associated with solar climatology. The solar researcher is more interested in scientific understanding than forecasting; the solar technologist is more interested in correct forecasting than scientific understanding. This twofold classification of users essentially decomposes the problem of determining requirements for resource data into two relatively independent subproblems. On the one hand, forecasters (application planners, system developers, utility grid operators, etc.) are users of the routine network, need site-specific forecasts of future solar climatic conditions, and generally require only moderate accuracy in the measurement of global, direct and/or diffuse solar radiation on a horizontal surface. In contrast, scientists are users of the much smaller research network, are concerned with discovering general laws (and associated models) governing solar climatology (as opposed to site-specific conditions), and need highly accurate and simultaneous measurement of several geophysical parameters. These parameters include

- (1) Insolation (direct, global)
- (2) Ambient temperature
- (3) Relative humidity
- (4) Turbidity
- (5) Pressure
- (6) Latitude
- (7) Surface elevation
- (8) Albedo
- (9) Spectral distribution of energy
- (10) Parameterized cloud cover.

A Definition Plan of Solar Radiation
Data Quantity and Quality Requirements

As noted previously in this report, it is acceptability of forecasts for use in evaluating expected performance of solar energy conversion

systems that should be taken as the principal criterion in determining network requirements. It follows from this assertion that the determination of solar radiation data needs should consist of simultaneously optimizing the routine network of stations and the forecasting methods to be used in characterizing future solar radiation environments. The significance of this dual optimization problem can be viewed in perspective of the practical limitations of network expansion and, hence, on the consequent operational constraints for the solar energy technologist. In particular, because of the necessary restriction to the number of routine stations, it is Battelle's view that the solar energy technologist must become accustomed to the fact that no station is likely to take the desired measurements at the desired time and place. Instead, the desired measurements must be estimated by interpolation using measurements taken at other stations at other times, and these results must then be forecast for the period of interest. Thus, to assure the full and rapid utilization of solar technologies, the solar technologist must be able to obtain valid interpolations and forecasts. If the methods for generating these results are simple, then the solar technologist should be provided with the methods. If the methods are not simple, he should be provided with the computed results, together with the historical "track records" of the methods used to generate the results.

The essential point implied by the above is that a specific rationale must be identified that would limit unwarranted expansion of the network. No matter how many stations are added to the monitoring network, someone's needs will not be met. In Battelle's view, no new routine network stations should be added to the existing network unless it can be demonstrated that such a station is cost effective and is essential in order to generate annual interpolations and forecasts with, say, 10 percent accuracy. Lacking such a criterion, proper evaluation of recommendations for expansion of the routine network is not possible. Exemplary of such recommendations requiring cost-effectiveness evaluation are those made in the 1973 Solar Energy Data Workshop. (20)

- (1) Adding new stations employing direct plus diffuse sensors in geographical areas of special interest such as regions of sharp gradients in average cloud cover (i.e., sea coasts).

- (2) Adding normal incidence and turbidity sensors to at least half of the 60-90 station networks.
- (3) Establishing new stations in regions of forecast population or industrial growth or at likely solar energy generating sites.

Further, the Conference on Solar Radiation Users⁽²¹⁾ in 1974 concluded that an acceptable network would provide pyranometer measurement and pyrliometer measurements at stations separated by no more than 200 miles or 300 miles, respectively, with sunshine recorders and satellites to be fully utilized for interpolation between stations.

Operational Goals for Determination of Network and Radiation Data Requirements

The above considerations lead to the following goals for resource assessment:

- (1) The routine network of stations should be designed to provide at minimum cost the data required to generate adequate forecasts of solar radiation properties. Suitable network design includes
 - Siting decisions for those stations judged as constituting cost-effective network additions.
 - Determination of data to be recorded at each station (hourly, total daily, direct, diffuse radiation, etc.) and concomitant instrument requirements.
 - Development of systems and procedures for quality assurance (maintenance of instrument calibration, data editing, etc.).
- (2) The forecasts must be obtained by spatial interpolation and temporal extrapolation using quantitative methodologies (models) which, in turn, are based on limited data from the network stations, possibly augmented by limited data from mobile units, balloons, aircraft, or satellites.

These goals raise the following kinds of questions:

- (1) To what extent does the existing network and its historical data provide adequate data for forecasting?
- (2) If adequate data are not provided, what minimal expansion of the entire network is required?

These questions cannot be answered until a wide variety of more specific questions are asked and answered. For example, what solar radiation properties are to be forecast? For what future time period? For what location? As a simple illustration exercise, suppose it is required to forecast the 1977 annual total horizontal radiation for each of the existing network stations using a methodology that is based on data available through 1976 for the remaining stations. Does there exist a methodology that will yield the total radiation within 10 percent (within 5 percent) for each network station? If not, where should additional stations be located? What measurements should be taken at these stations? How frequently? With what accuracy?, etc. Correspondingly, a basic interpolation and forecast problem can be stated as follows: Suppose no climate data are available for Station X. However, monthly average measurements are available for a two-year period on

- Total insolation
- Sunshine
- Turbidity
- Air temperature
- Pressure
- Relative humidity
- Wind speed
- Wind direction
- Cloud cover
- Precipitation

for horizontal surfaces at five stations in the same geographical region as Station X. Each station has a known latitude, longitude, elevation, and distance from Station X. For Station X, compute the expected annual average for each of the variables listed above and give a confidence interval for the forecast.

A Recommended Procedure for Determination of Forecasting Methods and Associated Network Requirements

Perhaps the most fundamental finding of this preliminary investigation is that, at present, no substantive analytical results exist on the basis

of which the suitability of available radiation data can be assessed. Accordingly, and in line with the goals and constraints stated above, Battelle concludes that the most pressing need consists of determining the precision with which forecasts can be made for selected cumulative and noncumulative solar radiation cases. These cases should include problems of site-specific temporal extrapolation and between-site spatial interpolation. Accordingly, Battelle recommends that methods of alternative levels of sophistication be developed and applied to the following five verifiable forecast problems:

- (1) Determine the expected accuracy and precision of annual forecasts based on extrapolation of the monthly insolation totals for the equinox months (March, September). This should be done using historical data of one year to "forecast" known results for the following year. If the accuracy and precision are acceptable, these results may indicate that mobile units could yield acceptable estimates of annual averages from samples taken during these two months of the year.
- (2) Suppose K stations are located within a climatically homogeneous region. Forecast the annual insolation totals for each of the K stations by interpolation of the historical data from the current year using the remaining (K-1) stations in the region. The procedure should be repeated for each region. These forecasts would constitute relatively simple forecasting problems because no extrapolations to future times are required and no interpolations to locations without measurement stations are required.
- (3) Extend the homogeneous region interpolation problem as described in (a) to include forecasts of insolation totals for future times. That is, the forecasts would be made for future times at each station using past historical data at the remaining (K-1) stations.
- (4) Extend the homogeneous region interpolation problem as described in (2) to include forecasts for selective sites for which recorded radiation data do not exist. That is, in this instance, the forecasts would be interpolated for selected locations that do not have measurement stations. Current data for the K stations would be used to generate the current year's "forecasts".
- (5) Extend the off-station site interpolation problem described in (4) to include "forecasts" for future time periods. That is, in this instance, both interpolation among existing stations and extrapolation to "future" times would be used to generate the "forecasts".

It is expected that the results of these increasingly difficult forecasting problems will consist of establishing, by numerical example, whether the existing network can provide forecasts that are sufficiently accurate and precise for engineering applications of solar energy conversion technologies. If no forecast deficiencies are found, then the existing network would be taken to be adequate. If forecast deficiencies are found, then it is expected that the kinds of deficiencies identified would indicate the augmentation modes required for the existing network. That is, the number and location of additional stations required to yield adequate forecasts for engineering applications would be identified by the results obtained from these problems. Recommendations of such augmentation would finally be based on the most cost-effective, minimal extension of the routine network that would be expected to yield acceptable forecasts. Specifically, the following kinds of extensions, both individually, and in combination with one another, would be considered:

- Addition of a station to the network, including location, type of measurements to be taken, when station operation should begin and how long the station must operate to yield desired accuracy of forecasts.
- Addition of more precise instrumentation at an existing station or stations, with complete identification of type of instrument, calibration procedures required, temperature response corrections, checks for degraded performance, frequency of calibration, etc.
- Determination of the optimum combination of additional stations and/or upgraded instrumentation.
- "Demonstration" of performance of the augmented system using hypothetical data from the optimizing combination of stations and upgraded instrumentation.
- Making realistic studies of costs associated with augmenting the existing system.
- Assessment of the additional benefit to the total existing network that would be expected by adding the optimizing combination of stations and upgraded instrumentation.

Methodological Approach for Treating the Forecast Problems

Both statistical and conceptual methods will be used in solving the above described forecasting problems. Statistical methods, such as regression analysis, general least squares, etc., will be sought which maximize the signal-to-noise ratio in accounting for identifiable components of variance in each of the forecast problems. The coefficient of determination (R^2) will be taken as the most appropriate criterion, and, hence, as an indication of the precision with which forecasts can be made. Conceptual methods, including time series analyses, exponential smoothing, etc., will be sought which best quantify the auto-correlational structure of data at specific sites and between sites. These structure auto-correlations will constitute the main components of methods for spatial interpolations.

In addition to the formulistic approach outlined above, the development of methods suited to each of the five forecast problems will also expose and treat a number of practical difficulties associated with the analyses radiation data. The difficulties include the following:

- (a) Historical data are available on some, but not all, variables.
- (b) Different variables may have different record lengths.
- (c) Some of the data on some variables may be missing.
- (d) Some values of some variables may be erroneous.
- (e) Little or no data exist at the site of interest.
- (f) Little or no data exist on the general terrain, climatology, etc. of the sites involved.

A possible methodological product emanating from this effort would consist of a family of Bayesian estimators for site-specific forecasts of future solar radiation characteristics. Such Bayesian forecasts would have the property that the statistical estimator of a given site-specific future radiation characteristic (say total radiation for the month of January) would consist of a weighted combination of (a) temporal extrapolation of historic data collected at the site and (b) spatial interpolation of data and/or

forecasts of the given characteristic at other climatically homogeneous sites. The development and application of a Bayesian forecast method having the above properties would, thus, yield regionally consistent estimates of radiation characteristics across

- Sites having permanent stations as part of the routine network and which record data on all primary geophysical parameters of interest.
- Sites where data are recorded regularly on some, but not all, parameters of interest, or where data are recorded for only selected discrete time periods (e.g., by means of mobile units).
- Sites where radiation data are not collected either on a regular or temporary basis.

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