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Availability of Direct Normal Radiation for Solar Furnace Processing: A Case Study

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AVAILABILITY OF DIRECT NORMAL RADIATION FOR SOLAR FURNACE PROCESSING: A CASE STUDY

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ABSTRACT

Predicting the availability of direct normal solar radiation is important for scheduling tests and estimating economics of solar furnaces. This paper looks at historical hourly average direct normal data to predict seasonal trends and report historical availability. Data collected at the Solar Radiation Research Laboratory (SRRL), located within 100 meters of the National Renewable Energy Laboratory's (NREL's) High-Flux Solar Furnace (HFSF), are analyzed to determine availability of the furnace for testing and processing samples.

The design of NREL's solar furnace allows considerable flexibility in processing samples under solar radiation levels of 100-1100 W/m^2. Flux levels of 1-2000 W/cm^2 can be delivered and controlled. Different processes pose different requirements for both incident flux and time.

The historical data for this site show how often the hourly average direct normal solar radiation is above a certain threshold over the period 1981-1992. Results also show how many tests could have been completed (or samples processed) using five-minute data from 1992. Effects of Mt. Pinatubo are also assessed.

1. INTRODUCTION

The primary purpose of this paper is to study the hourly direct normal data collected at the Solar Radiation Research Laboratory (SRRL) to determine how the resource affects the availability of NREL's High-Flux Solar Furnace. The SRRL hourly solar radiation data are discussed in detail in a report by Marion [1]. This paper will address the following issues: the quality and quantity of data in the data base, the range of requirements for potential furnace applications, the assumptions and limitations of this study, and the analysis of the data base to determine the availability of the furnace.

2. THE SRRL DATA BASE

The SRRL data base contains approximately 25 elements including 20 which relate to solar radiation and 5 relating to meteorological measurements. The data represent hourly averages of five-minute (one-minute data prior to 1984) data recorded at the SRRL site on South Table Mountain in Golden, Colorado. The five-minute data are an average of samples taken at 10-second intervals. If more than ten minutes of data out of the hour were missing, the average was not computed and the datum was recorded as missing.

The data acquisition system and all instrumentation are maintained on a daily basis (except weekends and holidays) and calibrated annually. The data are checked using a post-collection quality assessment (QA) procedure. Three tests using SERI QC software [2] assess the quality of the direct normal radiation data. The tests compare K_n, the direct normal transmittance, K_t, the global horizontal transmittance, and K_d, the diffuse horizontal transmittance, to determine if they fall within reasonable limits. Data that do not pass the above tests are assigned a flag that indicates which test the data failed and the magnitude of the outlier. 0.3% of the data failed the one-element test, which checks the K-factors above individually. In the two- or three-element tests, two or three of the above K-factors are checked together and passed if within 0.03 "K-units" of the acceptable range. 2.1% of the data failed the two- or three-element test by greater than 0.05 K-units. All data are used in this paper unless otherwise noted.

Figure 1 is taken from Marion [1] and shows the percentage of daytime data collected and passing QA. The data up to 1992 come from the same report. The

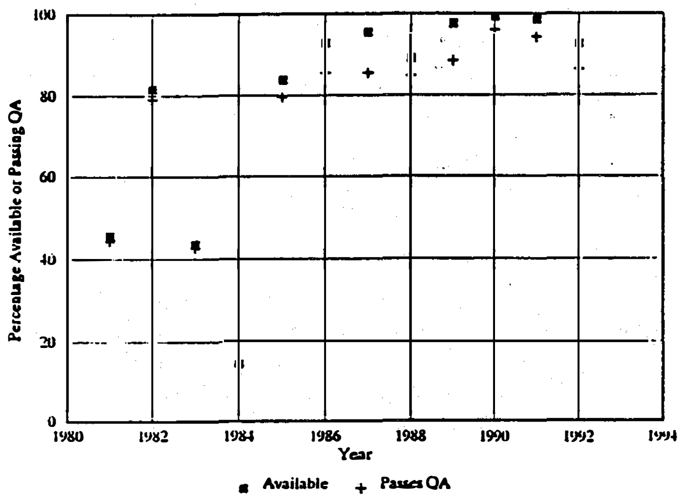

Fig. 1. Direct Normal Data Availability–1981-1992. Data for 1991-1981 are percentage of daylight hours from Marion [1]; the 1992 data are percentage of total hours.

1992 data on Figure 1 are the percentage of all data missing and percentage of available direct normal data passing QA. The data contain sizable gaps, including several months in which a significant portion of the data are missing. The remaining QA data in this report are the percentage of available data and do not include missing data.

3. SOLAR FURNACE PROCESSES

The High-Flux Solar Furnace at NREL is designed as a faceted concentrator with an attenuator to provide flexibility in the amount of flux delivered at the focal point. The faceted primary concentrator can produce flux levels up to 2500 times the direct normal radiation. With the addition of a non-imaging secondary concentrator, flux levels 21,000 times the direct normal are achievable [3]. For most processes, the flux available at the focal point is approximately 1-2000 W/cm^2. With a lower level of direct normal radiation, we either uncover facets of the primary concentrator or open the attenuator to provide additional flux at the focal point. Tests have been run with levels of direct normal radiation less than 100 W/m^2.

Different applications have different requirements for direct normal radiation. The most difficult requirement is maximum flux uninterrupted over several hours. Some processes operating at temperatures above 1200°C require the maximum power (10 kW) of the furnace and are hampered by reductions in the radiation level. Fortunately, most of these processes last only a few minutes. In order for such a process to be economically viable, the product must have considerable value. On the other end of the spectrum, some processes are very forgiving, requiring minimal flux whenever it is available. Most processes lie somewhere in between—requiring less than full power, and able to tolerate interruptions due to either thin or small clouds.

4. ASSUMPTIONS AND LIMITATIONS

This study has several assumptions and limitations. The first is that the available data are averaged over an hour, and therefore, short interruptions of solar radiation are masked. This limitation primarily impacts processes that are adversely affected by the intermittent clouds masked by the averaging.

Secondly, for the purpose of this analysis, missing hourly data are assumed to be distributed in the same manner as the existing data. For the five-minute data in 1992 used to examine the number of tests which could be completed, the missing data are assumed to be 0.0 W/m^2.

Other issues—not included in the following analysis—may affect the availability of the furnace. If aiming is not critical, some tests may be completed with wind velocities of up to 10 m/s, whereas other tests would have to be terminated with wind velocities of less than 5 m/s. Other factors affecting availability could be extremely cold ambient temperatures (-20°C), problems with equipment, or time required for setup and removal of experiments. Finally, this analysis is only applicable to this site.

5. RESULTS

The results are grouped into four analyses: the first three use hourly average data to examine long-term availability, seasonal variations, and effects of Mt. Pinatubo; the last analysis uses five-minute average data from 1992 to examine the number of tests that could be completed during the year.

5.1 Long Term Availability

The first analysis of the data shows how many hours each month the direct normal was above a certain threshold over the period of record. Data are available for 1981-1992. Figure 2 shows the percentage of monthly hours above 1000 and 500 W/m^2 average direct normal radiation. The effects of El Chichon in 1982 and Mt. Pinatubo in 1992 are both easily observed.

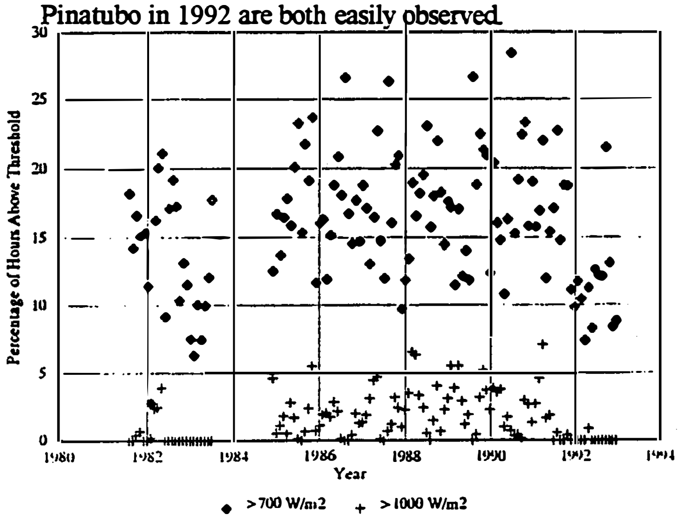

Fig. 2. Percentage of Hours per Month Average Direct Normal Radiation over 700-1000 W/m^2 for 1981-1992.

TABLE 1
Long-Term Direct Normal Thresholds

Threshold (W/m^2)	Hours/month above threshold (percent of total hours/month) 1985-1990	All years
100	251 (34.4%)	244 (33.4%)
200	226 (30.9%)	218 (29.8%)
300	204 (27.9%)	196 (26.8%)
400	186 (25.5%)	177 (24.2%)
500	167 (22.9%)	158 (21.6%)
600	149 (20.4%)	139 (19.0%)
700	129 (17.7%)	117 (16.0%)
800	103 (14.1%)	99 (13.6%)
900	67 (9.2%)	53 (7.3%)
1000	15 (2.1%)	11 (1.5%)
Missing*	50 (6.9%)	53 (7.3%)
Passed QA	89.4%	90.1%

*Missing data assumed to be randomly distributed

Table 1 shows the long-term availability as expressed by the average number of hours per month that the hourly average direct normal is above a certain threshold. Data are shown for the entire period of record, as well as the 1985-1990 period between volcanic eruptions. For the entire period of record, 90.1% of the available data passed QA.

5.2 Seasonal Variations in Direct Normal Radiation

To determine seasonal variations in direct normal radiation, we display the data somewhat differently. Figure 3 shows the average and standard deviation of the 700-W/m^2 line from Figure 2 over the years 1985-1990, displayed as a function of month of year. This period was chosen for this analysis to eliminate the effects of the volcanic eruptions. Excluded from this plot are months in which over 25% of the data did not pass QA. Over the six-year period, the following months were excluded: March 1988, May 1985, June 1987, July 1986, October 1985, and November 1985 and 1987. Thus, monthly values vary significantly from year to year.

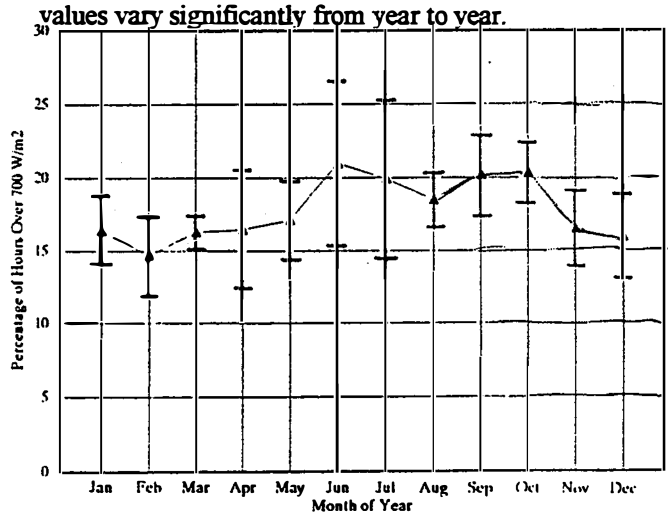

Fig. 3. Seasonal Variation in Direct Normal Radiation over 700 W/m^2, 1985-1990. Average and standard deviation are shown for each month. Months in which 25% of the data fails QA are excluded.

Table 2 shows the six-year average of the data in Figure 3, along with values for 500, 900, and 1000 W/m^2. The variance and range of values are also included in the table.

This analysis highlights the seasonal variations, as seen in Figure 4. Whereas the 500-W/m^2 line in Figure 4 shows the effect of the longer days in the summer, the 1000-W/m^2 line shows a remarkable dip in the summer; over the six-year period, the worst time of year for high direct

TABLE 2

Seasonal Variations 1985-1990

Month(*)	500	700	900	1000
	Percentage of hours direct normal (W/m²) above threshold			
January (6)	19.6	16.4	9.4	3.0
February (6)	19.2	14.7	8.5	3.5
March (5)	20.6	16.3	9.1	3.2
April (6)	22.8	16.5	9.1	2.9
May (5)	23.0	17.1	7.9	1.5
June (5)	28.5	21.0	9.1	0.7
July (5)	26.5	19.9	7.1	0.2
August (6)	26.1	18.5	8.0	0.7
September (6)	26.0	20.2	11.2	2.2
October (5)	23.9	20.3	12.1	2.7
November (4)	21.1	16.5	9.6	2.5
December (6)	19.1	16.0	9.5	1.9
average	23.0	17.8	9.2	2.1
variance	9.4	4.0	1.8	1.1
highest	37.0	28.5	14.7	6.6
lowest	13.8	10.9	2.4	0.0

* number in parentheses is number of months the data are averaged over

normal values is the summer! The apparent reduction in clear skies in the summer is due to the increased moisture in the atmosphere at that time. The least amount of atmospheric moisture occurs in the fall at this site. The trends of the 700- and 900-W/m² lines indicate the fall months are somewhat clearer than the other months.

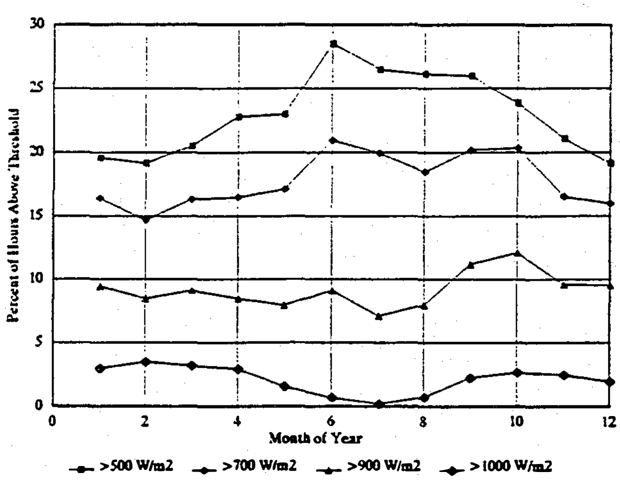

Fig. 4. Seasonal Variation in Direct Normal Radiation. Average per month over 500-1000 W/m² for the period 1985-1990. Months in which 25% of data fails QA are excluded.

5.3 **Effects of Mt. Pinatubo**

The effects of the eruption of Mt. Pinatubo in June 1991 were first seen in Denver around August 1991 [4]. Table 3 shows the average hours above threshold for the 17-month period after August 1, 1991. Also shown is the ratio of hours/month above the threshold before and after the eruption. For the 17-month period after the Mt. Pinatubo eruption, 93.2% of the data available passed QA.

TABLE 3

Hours Above Threshold After Mt. Pinatubo

Threshold (W/m²)	Hours/month above threshold (%)	Ratio before/after
100	232 (31.7%)	1.08
200	202 (27.6%)	1.12
300	179 (24.5%)	1.14
400	160 (21.9%)	1.16
500	140 (19.1%)	1.20
600	116 (15.9%)	1.28
700	91 (12.5%)	1.41
800	57 (7.8%)	1.81
900	17 (2.3%)	3.96
1000	0.5 (0.07%)	30.0
Missing	43 5.9%	
Passed QA	93.2%	

*Missing assumed to be randomly distributed

Figure 5 shows the percentage of hours the direct normal radiation was above a certain threshold during 1985-1990 and the 17-month period. Note that the percentages at

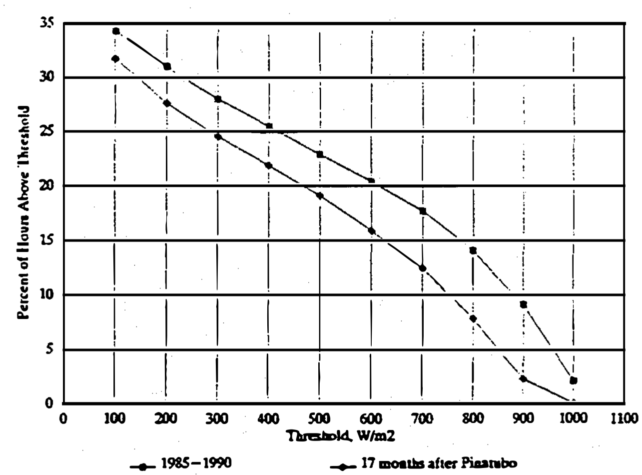

Fig. 5. Effect of Mt. Pinatubo. Direct normal availability between 1985-1990 versus 17 months after August 1, 1991.

each threshold were reduced dramatically. For example, the number of hours per month the average direct normal exceeded 900 W/m^2 was reduced 75%, from 67 to 17 hours/month before and after the eruption, respectively.

5.4 Number of tests possible

For tests which require continuous radiation (i.e., no tolerance to clouds), we looked at availability data with respect to time, e.g., we determined how many two-hour periods there were each month with average direct normal continuously over 700 W/m^2 there were each month.

The best data to use are five-minute averages instead of one-hour averages, because many tests last less than one hour. Only one year (1992) of five-minute data was used for this analysis—the period when the effects of the Mt. Pinatubo cloud were evident. There are no QA flags for the five-minute data, but from the hourly averages, 93.7% of the data available pass QA. Missing are 7.6% of the five-minute data, which for this analysis only are assumed to be 0.0 W/m^2.

We calculated the number of tests by counting consecutive five-minute periods in which the average direct normal was above a certain threshold. Table 4 shows the average number of five-minute to eight-hour tests per month which would have been possible in 1992, as a function of the direct normal solar radiation threshold required to initiate the test. These data are low because any missing data would cause a period not to be counted.

TABLE 4
Possible Tests per Month in 1992

Threshold	Test Length (minutes)						
(W/m^2)	5	15	30	60	120	240	480
100	2192	682	314	138	55	20	5
200	1979	612	282	123	50	18	4
300	1798	554	254	109	43	15	3
400	1631	501	228	97	38	13	2
500	1449	443	199	84	32	10	1
600	1240	376	167	71	27	8	1
700	978	293	130	54	19	5	<1
800	596	177	77	31	10	2	<1
900	104	30	13	5	1	<1	0

Missing data (7.6%) assumed to be 0.0 W/m^2

The number of tests which could be completed after Mt. Pinatubo clears can be estimated by applying the ratios before/after in Table 3 to the data in Table 4. The result is shown in Figure 6.

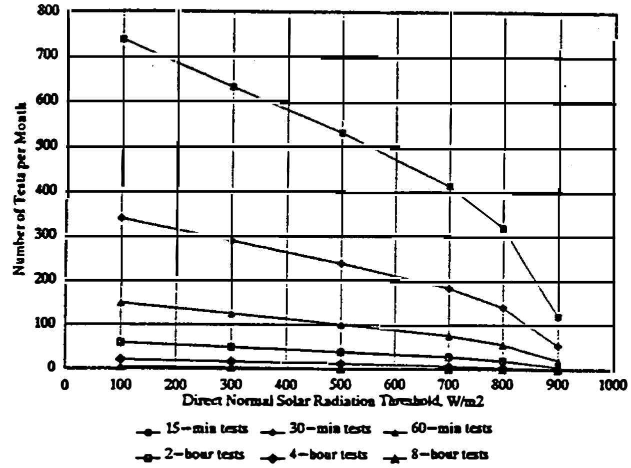

Fig. 6. Number of Tests Possible per Month. Uses 5-minute data from 1992. Data adjusted for Mt. Pinatubo loss per ratios in Table 2. Missing data are assumed to be 0.0 W/m^2.

If a test can tolerate clouds, the results from a lower threshold would give an indication of the number of tests. For example, if the process requires 800 W/m^2 and can tolerate clouds, the number of tests per month would likely fall between the values for 700 and 800 W/m^2.

6. CONCLUSIONS

The key conclusion of this study is the dramatic impact of the Mt. Pinatubo eruption on direct normal solar radiation. Four times as many hours with an average direct normal radiation over 900 W/m^2 occurred before the eruption than after.

One of the motivations of this study was to answer the often-asked question, "How often is it sunny enough to run a test?" If we assume a test requires an average of only 700 W/m^2 direct normal radiation, then approximately 16% of the hours of the day will be suitable for testing. If we assume that half of the hours of the day occur during daylight, then 32% of the daylight hours are suitable for testing. On the other hand, daylight hours averaging over 500 and 900 W/m^2 occur about 43% and 14% of the time, respectively. As half of the daylight hours are unsuitable for most tests, it is very important to be ready to test when conditions are suitable.

Some significant conclusions can be made about how to make the best use of a solar furnace. The more we can make use of lower levels of solar radiation, the more times we will have for processing or testing. From the data showing hours per month above certain thresholds, if a process can use 700 W/m^2 direct normal radiation instead of 900 W/m^2, we have more than twice the available time for testing.

The flexibility of NREL's solar furnace allows us to use low direct normal radiation for many of our tests. Even with 500 W/m^2, concentrations of 2000-20,000 allow us to provide 100-1000 W/cm^2 at the focal point. A test requiring maximum flux usually requires high levels of direct normal solar radiation and will have fewer opportunities for testing.

Also, if testing requires no cloud interruptions, the periods for testing are infrequent for tests that last several hours. There will be more opportunities for testing if the process has a tolerance to small clouds.

The study of seasonal variations yielded some surprising results. The summer months provided the least clear days. During the summer, a significant dip occurred in the percentage of hours the average direct normal was above 1000 W/m^2, for the 1985-1990 period analyzed. Direct normal solar radiation for testing in the fall was surprisingly good at all levels. Processes requiring lower levels of direct normal radiation have more hours for testing available in the summer due to the longer days. While summertime will have more daylight hours, skies in the spring, fall, and winter are clear enough to compensate for the shorter days.

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