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PRELIMINARY
DEFINITION OF BARSTOW
STANDARD CLOUD MODEL

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FOREWORD

This report is written as a partial account of work performed for the Department of Energy, on the 10 MW Solar Thermal Pilot Plant Project, under Contract Number E(04-3)-1101, Project Agreement No. 2.

TABLE OF CONTENTS

	<u>Page</u>
FOREWORD	i
1. INTRODUCTION	1
2. CLOUD DESCRIPTIONS	2
3. PROBABILITY OF CLOUD COVER	7
4. FIELD POWER COMPUTER ANALYSIS	11
5. RECOMMENDED CLOUD MODELS	15
6. CONCLUSIONS	18
REFERENCES	19

1. INTRODUCTION

The motion of cloud shadows across a collector field for a central receiver solar power plant can affect the design of such a facility in several ways. Sharp shadow edges can produce large temperature gradients in the receiver structure and in the flow medium which induce thermal stresses within the structure and variations in the steam flow and temperature within the components of the steam cycle. The repeated motion of these cloud shadows will cause thermal cycling of the receiver, possibly leading to fatigue failure. Finally, the motion of cloud shadows across the field must be considered in the design of the control systems.

The objective of this study is to develop cloud models to be used for basis of design in the technology areas noted above. The first effect, that of the temperature gradient, is simulated by postulating the worst case cloud situation. The cyclic effects require realistic cloud shadow time histories for simulation.

The study approach is outlined below:

1. Cloud shadow models are developed to determine probable cloud type, the cloud area and shape, cloud velocity and cloud-to-cloud spacing. (Section 2)
2. The probability of cloud occurrence is estimated. (Section 3)
3. A collector field computer program is run to determine the effect of cloud variables on collector field power delivery capability. (Sec. 4)
4. Recommendation of cloud models to be used for basis of design are then made. (Section 5)

2.0 CLOUD DESCRIPTIONS

There are six factors which influence a cloud shadow model. These are: the cloud type, the cloud area and shape, the cloud-to-cloud spacing, the frequency of occurrence of clouds, the sun-cloud geometry, and the cloud velocity vector.

2.1 Cloud Types

The cloud type is important in that only a limited number of cloud types can produce sharp shadows on the ground. In general, ice clouds do not have sharp edges since there is a gradation of conditions at their edges. Water clouds tend to have sharply defined boundaries. High clouds will not produce sharp shadows because of the finite size of the sun. The diameter of the sun is approximately 0.01 radians. A cloud at 5000 feet will have the transition from shadow-to-bright spread over 50 feet due to the sun's finite size, while a cloud at 20,000 feet will have a transition of 200 feet. For these reasons only limited extent water clouds with bases below 5000 feet have been considered for maximum power gradient problems. These cloud types are: cumulus, stratocumulus, cumulonimbus, and altocumulus.

2.2 Cloud Data

Statistics of cloud sizes, shapes, and spacings at the plant site are not available. Several sources of plant data are available for other sites, and the cloud model was developed to be compatible with this data. The modeling was developed first to determine a maximum gradient cloud and the model was further refined to determine frequency of occurrence.

2.2.1 Maximum Gradient Cloud

One source of cloud data is the information contained in Reference 1. This report contains cloud speed and cloud size frequency distributions are for cloud observations in Tucson, Arizona, taken over an eight month period. They are reproduced in Figure 1. Referring to Figure 1 it appears that clouds larger than the pilot plant heliostat field are quite likely. The pilot plant heliostat field is approximately 0.40 km in diameter and it can be estimated that over 95 percent of all clouds will be larger than this. Based on this data the cloud model can be

(a) CLOUD SPEED

(b) CLOUD SIZE

Figure 1. Representative Cloud Speed and Size Probability Density Functions (Based on Tucson, Arizona data)

simplified by assuming a single cloud moving over the field is an adequate representation of actual expected conditions. The cloud speeds reach a maximum of 54 km/hr. (Reference 2)

A parametric analyses of variation of cloud cover and speed, developed in Section 4.0, will yield the design cloud producing maximum temperature gradients.

2.2.2 Cloud Frequency

Cloud frequency data is needed for control system and material fatigue studies. Information on cloud frequencies can be derived from the cloud data reported in Reference 2. In this report a cloud model was constructed based on several references concerning cloud statistics as determined from U-2 photographs. A cloud shadow field was modeled with the cloud shadows being represented as rectangles, where the ratio of the rectangle length to width was based on the cloud data. The probability of being in shadow can be estimated from cloud-free lines-of-sight studies. This has been studied as a function of elevation angle, cloud type, and cloud cover. The probability of a cloud-free line-of-sight may be interpreted as the fractional area of the shadow field not shadowed. The shadow fractions as developed in Reference 2 are repeated in Table 1.

The number of shadows of each size to be put in the shadow field is derived from the frequency of occurrence in total cloud area and plotted in Figure 2. The straight line approximations to this data for each cloud type of interest are given by:

Cloud Type 1	Cumulus humilis (fractus) $P = 36.144 - 16.256 \ln(A)$
Cloud Type 2	Cumulus mediocris (congestus) $P = 22.605 - 6.363 \ln(A)$
Cloud Type 3	Cumulonimbus culvus $P = 14.277 - 3.06 \ln(A)$

where P is the percent of the total cloud area to be represented by a cloud of area A, where A is in square kilometers. P and A are used to calculate the number of shadows of each area to be put in the shadow field.

The techniques to develop the shadow field is fully described in Reference 2 and is not repeated here. Examples of cloud shadow fields

TABLE I

TOTAL FRACTIONAL SHADOW AREA
FOR CUMULIFORM CLOUDS

Solar Elevation Angle θ	Sky Cover (Tenths)										
	0	1	2	3	4	5	6	7	8	9	10
90	0.01	0.06	0.12	0.17	0.22	0.26	0.32	0.44	0.59	0.75	0.97
80	0.01	0.06	0.12	0.17	0.22	0.26	0.33	0.44	0.59	0.75	0.97
70	0.01	0.06	0.12	0.17	0.22	0.26	0.33	0.45	0.59	0.75	0.97
60	0.01	0.06	0.12	0.17	0.22	0.27	0.33	0.45	0.61	0.76	0.97
50	0.01	0.06	0.13	0.17	0.23	0.28	0.34	0.46	0.63	0.78	0.97
40	0.01	0.07	0.14	0.19	0.25	0.31	0.37	0.50	0.66	0.81	0.98
30	0.02	0.08	0.16	0.22	0.29	0.35	0.43	0.55	0.71	0.84	0.98
20	0.02	0.11	0.20	0.27	0.36	0.43	0.50	0.63	0.76	0.88	0.98
10	0.03	0.15	0.27	0.34	0.46	0.53	0.61	0.72	0.83	0.92	0.99

Frequencies of Cloud Areas for Three Cumuliform Cloud Types

FIGURE 2

with various sky coverages are given in Figures 3 and 4. This data was used to define an intermittent cloud mode. Of course, this cloud model yields the cloud distribution for only that specific cloud cover type. It does not give us the probability of occurrence of that cloud cover type since, unfortunately, a coordinated set of data including cloud cover type as a function of time and solar elevation, cloud velocity, and cloud size distribution do not exist for the Barstow plant site.

3.0 PROBABILITY OF CLOUD COVER

Good statistics on cloud type, cloud velocity and sky coverage do not exist for the Barstow, California Pilot Plant location. What does exist is the insolation data taken at the site by Southern California Edison for the year 1976. An analysis of this data, summarized in Table 2, indicates that out of 3,378 insolation hours available annually, 1,382 of these hours, or 40.9% of the total insolation hours, there occurred moderate to heavy intermittent cloud coverage. Unfortunately, the majority of these intermittent cloudy hours occurred at mid-day during the time of the most useful insolation. Therefore, the percentage of intermittent operation during effective insolation time is much greater than the 40.9% noted above.

An augmented insolation data gathering program at the site would greatly improve this admittedly sketchy analysis. Multiple sensors located throughout the field would give information on cloud coverage, cloud size and cloud velocity. An instantaneous value of insolation rather than a 15-minute integrated solar energy measurement would also provide a clearer idea of the intermittent value of the insolation. Detail recommendations for an improved data gathering program are recorded in the conclusion of this report.

CASE NO. 22
CLOUD TYPE 1
SKY COVERAGE 0.2
SOLAR
ELEVATION 40.0

Figure 3. Cloud Shadow Field

Cloud Shadow Field

CASE No. 1
CLOUD TYPE 1
SKY COVERAGE 0.5
SOLAR
ELEVATION 40

FIGURE 4

TABLE 2.

PERCENTAGE OF MODERATE TO HEAVY INTERMITTENT
CLOUD COVERAGE AT BARSTOW, CALIFORNIA
(Based on SCE Insolation Data)

Month	Total Insolation Hours Available (all levels)	Intermittent Hours	Percentage of Intermittent Operation
Jan	248	178	71.7
Feb	232	133	57.3
March	248	113	45.6
April	270	131	48.5
May	279	158	56.6
June	330	189	57.2
July	341	116	34.0
August	341	18	5.3
Sept	330	179	54.2
Oct	279	63	22.6
Nov	240	43	17.9
Dec	240	61	25.4
Total Annual	3378	1382	40.9

4.0 COMPUTER FIELD-POWER ANALYSIS

Computer software has been developed at Aerospace which simulates various cloud models and calculates the effects of cloud motion on the energy output of a specific central receiver model. (See Ref. 2). The FORTRAN coded computer program (CLDSIM) is used to compute the re-directed power level as a function of time and determine probability statistics of the rate of change of received power. This rate of change of re-directed power to the receiver can be studied as a function of various parameters such as sky cover, cloud drift velocity, cloud type, and solar elevation.

4.1 Study Variables

The computer program has been used (previous to this study) to generate the rate of change of power with those parameters which characterize the geometry and dynamics of the cloud model. The parameters included:

- 1) Sky cover
- 2) Cloud type
- 3) Cloud velocity
- 4) Solar elevation

The study was performed for a collector field larger than that of the Pilot Plant, but the report trends are generally applicable. A functional relationship called maximum rate of change of power (MRCP) was developed to illustrate the dependence of the rate of change of power on these parameters.

4.2 Study Results

A set of typical or average values was adopted for the parameters, as well as a range for which they would be studied. Whenever the effects of a particular parameter were being investigated all other parameters were held at typical values. The typical or average value of the parameter and the range are noted below:

<u>Parameter</u>	<u>Average</u>	<u>Range of Study</u>
Solar Elevation	40 degrees	20 to 80 degrees
Sky Coverage Fraction	0.5	0.1 to 0.8
Draft Velocity	36 km/hr	18 to 54 km/hr
Cloud Type	Type 1	Type 1 to 3

4.2.1 Results for Maximum Rate of Change of Power (MRCP)

- The MRCP is moderately dependent on sky cover. Even low values of sky cover is likely to contain cloud shadows larger than the collector field thereby producing, at equal cloud velocity, equivalent MRCP.
- The MRCP is essentially independent of the cloud type.
- The MRCP is linearly dependent on cloud velocity. This parameter has the greatest effect on MRCP. For the Pilot Plant the MRCP corresponding to a cloud velocity of 42 km/hr, (the maximum wind velocity at which the plant is to remain operational) is 1.2 MWt/sec.
- The dependence of the MRCP on solar elevation is minor and approximately monotonic.

For detailed numerical results refer to Reference 2.

4.2.2 Number of Cycles on Receiver Due to Clouds

For Pilot Plant design purposes an estimate can be made of the number of unexpected thermal cycles (assumed to be due to clouds) that would have been experienced by a central receiver at Barstow, California during 1976. Since there is no reliable cloud data available at the site, this estimate is based entirely on an examination of the direct normal insolation data compiled in Reference 3. The examination is based on the following definitions and assumptions:

- (1) A thermal cycle is defined as the occurrence of two events which would take the receiver from a high flux level to a lower flux level and return it to a high flux level. The events are defined below.
- (2) The first event in a cycle occurs when at least 700 watts per square meter insolation is available and the insolation drops by at least 100 watts per square meter. Since the insolation data is taken by

measuring the total energy available in a 15 minute interval, the counting of events shorter than that interval is not possible.

- (3) The second event in a cycle occurs when sufficient insolation is available to restore the receiver to temperature. The data given here is done by counting events. The number of cycles is half the number of events.
- (4) It is assumed that at the plant observations of cloud conditions are carried on and that decisions based on those observations and predictions can be made to permit operations which will minimize the thermal cycling of the receiver when little or no significant energy can be collected. Thus:
 - (a) Events are not counted on any day unless at least one or two hours of clear operation is possible. This eliminates days of very poor insolation.
 - (b) If a long period of clear insolation is preceded by or followed by a long period of cloudiness only one event is counted.
- (5) It is assumed that operational decisions are made based on time of day.
 - (a) The plant would not be started until at least an hour of clear weather appears to be available.
 - (b) If a cloud or group of clouds hit within approximately an hour of sunset, normal plant shutdown would be initiated.
- (6) Events are not counted during startup and shutdown periods when overall insolation requirements are low.
- (7) It is assumed that cycling occurs either because it is unexpected or it is tolerated because a significant level of energy is still available in the day.

Based on the above criteria 481 events were counted during the year 1976. This implies that the receiver would experience approximately 240 abrupt or "unexpected" cycles in a year. This factor should be added to the planned or "predictable" number of cycles in consideration of thermal fatigue problems.

A great deal more data is required to get a more reliable estimate of the frequency of thermal cycling due to clouds. The technique used here is admittedly very subjective, but for the present can be used as a reasonable guideline.

5.0 RECOMMENDED CLOUD MODELS

A high gradient cloud model and a cloud frequency model were developed for basis of design of high thermal gradient and thermal cycle problems.

The single cloud model has been developed for basis of design in regard to thermal shock, thermal stress and fluid flow analysis. The model shown in Figure 5 yields the maximum rate of power change to the receiver in both the cloud on and off transition. The design cloud is a water cloud with a base below 5,000 ft. which has sharply defined boundaries. The cloud is larger than the pilot plant heliostat and, therefore, the assumption of a single cloud moving over the field is an adequate representation of actual expected conditions. The cloud velocity is 42 km/hr., the highest wind velocity in which the plant is expected to remain operational.

The direction of the single cloud shall be from the north, south and from the west since the pilot plant design and performance is directionally dependent. A cloud approaching from due north affects the boiler/superheated sections of the receiver first. A cloud from the southern direction affects the preheater; a westerly directed cloud has a tendency to dampen both.

The cloud frequency model is shown in Figure 6. This intermittent cloud model is to be used for basis of design of cycle fatigue and control system studies. The cloud characteristics are similar to the single cloud model except for its finite length. The model assumes a sky coverage of 50% and a solar elevation of 40° which yields a ground cloud coverage of 31%. The recommended cloud speed is the average wind speed at the site, 16 km/hr.

Figure 5. Schematic of Cloud Simulation.

Figure 6. Cloud Frequency Model

6.0 CONCLUSION

A cloud model has been developed for both receiver incident power gradient and intermittent power studies. The model indicates that the maximum gradient to be expected is approximately ± 1.2 MWt/sec.

This analysis was based on cloud data taken at other than the Barstow site. Due to the importance of these design factors, it is strongly recommended that a cloud data gathering effort be undertaken at the Barstow California site. Data required includes:

- (a) Instantaneous measurement of solar insolation flux.
- (b) Multiple measurements of insolation throughout collector field to determine cloud cover and cloud velocity.
- (c) Cloud type
- (d) Cloud direction
- (e) Assurance that only clouds are causing measured attenuation (i.e., not obstruction, instrument failures, etc.).

It is also strongly recommended that the cloud model be speedily incorporated into the computer pilot plant simulation to determine the Plant's sensitivity to the possible cloud patterns identified above.

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