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IEA/SPS 500 kW DISTRIBUTED COLLECTOR SYSTEM

by

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ABSTRACT

This paper reviews the results of engineering studies for an International Energy Agency (IEA) project for the design and construction of a 500 kWe (net) solar thermal-electric power generation system of the Distributed Collector System (DCS) type. The project is part of the IEA Small Solar Power System (SSPS) Project, and is being constructed as a demonstration plant in the province of Almeria in Southern Spain.

The DCS system design was completed by a 10 nation team headed by Acurex Corporation, a U.S. firm. Construction is presently underway. The design consists of a mixed field of parbolic trough-type solar collectors of both German and U.S. design which are used to heat a thermal heat transfer oil. Heated oil is delivered to a thermocline storage tank from which heat is extracted and delivered to a boiler by a second heat transfer loop using the same heat transfer oil. Steam is generated in the boiler, expanded through a steam turbine, and recirculated through a condenser system cooled by a wet cooling tower.

NOMENCLATURE

Symbols:

A_c = net collector area, m^2

c_p = heat transfer oil specific heat at average temperature

Δt_i = difference between the inlet and outlet temperatures of collector heat transfer oil

ΔT = mean fluid temperature in collector minus ambient temperature (260°C - 15.8°C = 244.2°C)

$\eta_{P.G.}$ = efficiency of power generation system

$\dot{m}$ = mass flow rate, kg/second

η = efficiency

ω = hour angle (solar noon is zero)

ϕ = latitude (north positive)

Q = rate of heat absorption by receiver tube

q_i = incident insolation, watts/m^2 collector

R_B = ratio of beam radiation on the reflector aperature to that on a surface normal to the beam

δ = declination (north positive)

INTRODUCTION -- THE IEA-SSPS-DCS PROJECT

The Small Solar Power Systems (SSPS) project is a program of the International Energy Agency (IEA). The program is intended to provide a solar-electric design suitable for both industrialized and developing countries in the range from 50 kW to 5 MW through a modular approach. The demonstration plant is presently under construction in the province of Almeria in Southern Spain. The Operating Agent for the IEA on the project is the Deutsche Forschungs- und Versuchsanstalt fur Luft- und Raumfahrt e.V. (DFVLR) a scientific and research agency of the German government. A consortium of Acurex Corporation and Tecnicas Reunidas (Spain), supported by subcontractors from eight other participating countries, conducted the detail design studies which are presented in this paper. The construction phase is being performed by a consortium of Acurex Corporation, M.A.N. Neue Technologie (Germany) and Tecnicas Reunidas with the support of firms from other participating countries.

The essential requirements for the design were:

1. Net output of 500 kW electrical at an insolation of 920 watts/m^2
2. Energy storage capacity of 0.8 MWh
3. Variable output from 10 percent to 100 percent of capacity whether grid-connected or operating independently of the electrical power grid
4. 2000 hours of operation annually at rated output

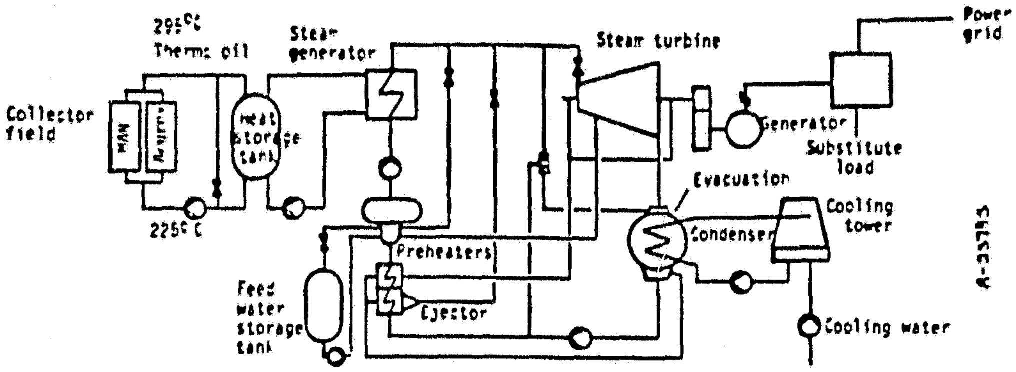

Figure 1. 500 kWe solar electric power generation system.

GENERAL ARRANGEMENT

The major subsystems for the DCS consist of the following, collector field, energy storage system, power conversion system, master control/data system, electrical system, roads and buildings, auxiliary equipment.

Two collector fields of approximately equal size are planned, with a total collector area of 4904 m^2. One field is made up of 10 loops of 48 collectors of U.S. design manufactured by Acurex Corporation and the other field is made up of 14 loops of six collectors of German design manufactured by M.A.N. Neue Technologie. The Acurex collector is single-axis tracking with the rotational axis oriented east-west. The M.A.N. collector employs two-axis tracking. The entire plant is fitted into an area 210 m east-west by 168 m north-south, including thermal storage and equipment. The system has been designed with three heat transfer loops. The first loop extracts low-temperature heat transfer oil from the bottom of the thermal storage tank, circulates it through the collector fields and returns it to the top of the storage tank. This decouples the solar fields from the power generation cycle but the power generation equipment can also be run directly from the collector fields if desired. (This connection is not shown on Figure 1.) The second loop extracts hot oil from the top of the storage tank, circulates it through the boiler and returns it to the bottom of the storage tank. The third loop circulates water through the boiler and then expands the steam through the turbine to extract energy for electrical power generation. The cycle is completed by condensing the expanded low-enthalpy steam and pumping the condensate back to the boiler. The thermal energy is converted to electrical energy by means of the steam turbine power conversion module (PCM). The process flow diagram, Figure 1, illustrates these loops.

The thermal energy is stored in an insulated tank 4.2 m inside diameter and approximately 15 m high, located near the power generation building. Various pumps, valves and auxiliary tanks are also located in this mechanical equipment area.

DESIGN ANALYSIS

System Sizing

The system design emphasized minimum capital cost; life-cycle costing has been performed but was not the primary criterion for equipment selection. Because of the high installed cost of solar equipment, the difference in optimization between a system based on life-cycle costs and one based on minimum capital cost is minimal.

The collector field size was calculated on the basis of parabolic trough concentrating collectors with glass reflective surfaces. The collector efficiency parametric equations used were as follows:

Acurex Collectors: $\eta = 0.756 - 0.57 \frac{\Delta T}{q_i}$

M.A.N. Collectors: $\eta = 0.685 - 0.435 \frac{\Delta T}{q_i}$

The design point was taken as the equinox noon condition, when the insolation is 920 watts/m^2. The incidence factor for both the Acurex and M.A.N. collectors is unity at the equinox noon design point. The calculated efficiencies are:

Acurex $\eta = 60.5$ percent
M.A.N. $\eta = 57.0$ percent

From these efficiencies, the field flowrate per loop is calculated so that the outlet temperature will be the desired 295°C.

$$\dot{m} = \frac{\eta q_i A_c}{\eta c_p \Delta t_i}$$

Acurex area = 267.7 square meters per loop
M.A.N. area = 192 square meters per loop
The loop flowrates are:
Acurex 0.778 kg/sec.
M.A.N. 0.523 kg/sec.

The flow requirement for the entire field is determined by the power generation cycle efficiency. With an efficiency of 0.2275 and a gross electrical output of 570 KW to allow for parasitic power, input to the power generation system must be 2507 KW. This is assumed to be accomplished in the steam generator at an efficiency of 99 percent. Since the temperature drop from the field to the steam generator is negligible (less than 0.5 degrees), the required output of the field is 2532 MW. The total flow requirement is computed as

$$\dot{m} = \frac{Q}{c_p \Delta T} = \frac{2532 \times 1000}{2729\ (295-225)} = 13.3 \text{ kg/second}$$

This requires 9 Acurex loops and 13 M.A.N. loops when the field is equally divided on an aperture area basis. The total flow is then 13.8 kg/second owing to the necessity to install discrete loops. To ensure adequate design margin, 10 Acurex loops and 14 M.A.N. loops will be installed.

Investigations were made of the effect of orienting the Acurex collector loop axes in various directions to peak their performance during different times of the year and thus equalize the field output over the year. The direct normal insolation that each collector orientation receives daily for the specified performance days is shown in Figures 2, 3 and 4 and illustrates the effect.

To determine the effect of various field orientations on the energy collected throughout the year, a tracking correction factor was derived. The tracking correction factor, R_b, is the ratio of beam radiation on the reflector aperture to that on a surface normal to the beam. Since Acurex collectors are one-axis tracking, the R_b factor is less than one. This factor is obtained from the following relations:

North-south orientation:

$$R_b = \left[(\sin\phi \sin\delta + \cos\phi \cos\delta \cos\omega)^2 + \cos^2\delta \sin^2\omega\right]^{1/2}$$

East-west orientation:

$$R_b = (1 - \cos^2\delta \sin\omega)^{1/2}$$

The optimum collector orientation is based on energy collected and compatibility of the collected energy and annual load distribution. In general, north-south tracking gives an advantage for summer peaked-load profiles and east-west tracking favors the winter. An E-W field orientation was chosen to provide a more even output over the year. However, a reduction in total annual operation time results.

Spacings and field arrangement (number of rows) of collectors determines their mutual shading and field pipe losses which in turn also affect the required collector field size. The shading losses for the parabolic trough Acurex collectors consists of the mutual shading of the adjacent collector and the shading due to the end supports for the receiver tube or self shading contribution due to mutual shading.

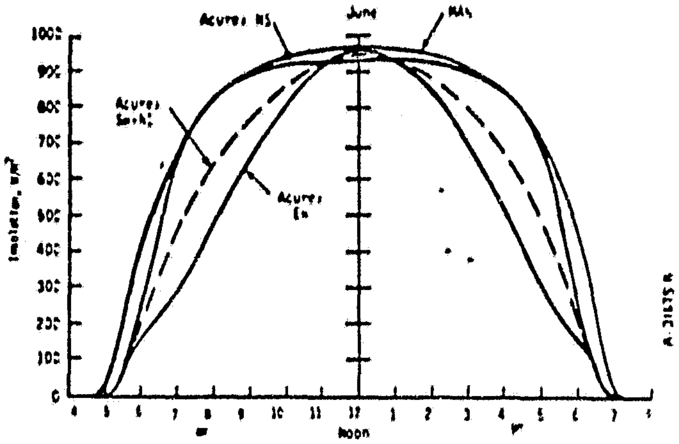

Figure 2. Effect of collector orientation.

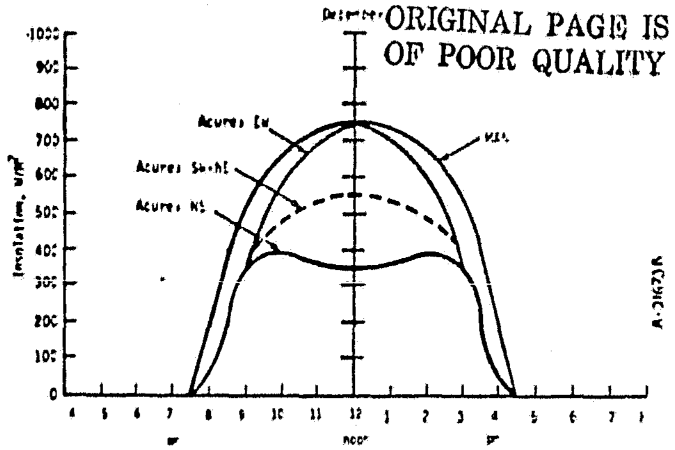

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Figure 3. Effect of collector orientation.

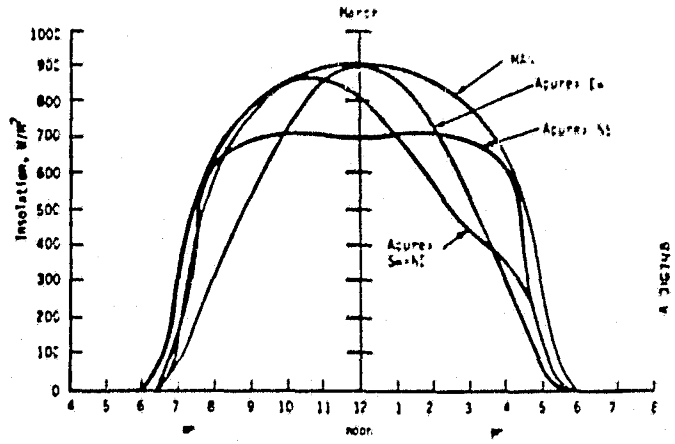

Figure 4. Effect of collector orientation.

The shading of the M.A.N collectors consists only of the mutual shading of adjacent collectors. The shading losses are tabulated below and shown by month in Figure 5.

POWER LOSS DUE TO SPACING (SHADING)

Month	A:NS	A:EW	MAN
Equinox	2.4%	0%	3.4%
Summer	0.98%	0%	2.2%
Winter	0.94%	0.76%	6.3%

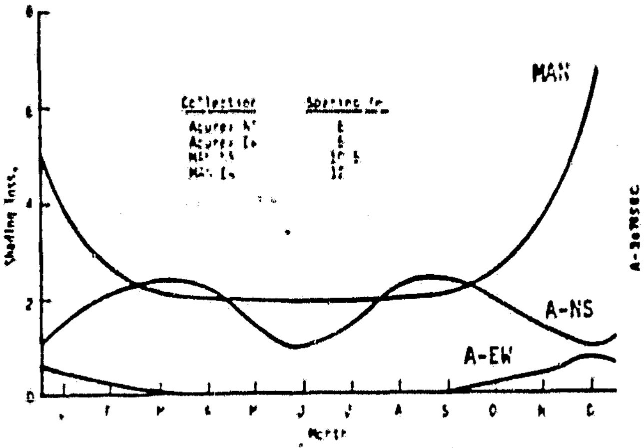

Figure 5. Monthly shading losses for the IEA collector fields.

System Performance

Analysis Methods. In evaluating the system, the SOLTAN code was utilized. In this code, a computation scheme making use of the collector thermal performance curve was the basis for the steady-state performance calculations. The SOLTAN code also calculated the transient performance of the stratified storage tank. The approach was Lagrangian.

Before the simulation of the final design configuration was performed, the insolation data file used in the SOLTAN calculation was modified to make use of the weather data for the actual site and the specified insolation levels. Making use of the data required selecting hourly data for 3-day intervals for each of the three months used in the simulation and interpolating these data to establish monthly insolation values for calculation of annual performance. The hourly system dynamic response was predicted for representative 3-day intervals during the year. This approach was adopted because: (1) hourly integration of the system response is required to represent the system transients properly; (2) calculations of system response for all 365 days of the year are prohibitively costly and unnecessary; and (3) three consecutive days were found to be long enough for the system to undergo many cycles of operation and provide results independent of the initial conditions for the calculations

The final task was that of defining the parameters which provide the system specification and corresponding performance. This involved utilizing the parameters for the power generation unit to establish the final collector field size and layout which necessarily resulted in the predicted performance of the final design.

To compute the transient behavior of the system, a different computer code was written. In this code, a separate subroutine exists for each component and, in some cases for the different functions of a component. The system components modeled were the collector field, consisting of the receiver tubes, manifold pipes, and connectors lines, the inlet buffer tank, and finally the flowrate control system.

Steady State Performance. The choice of operating temperature is closely tied to the availability of the working fluid and the overall system efficiency. System efficiency can be defined as:

$$\eta_{system} = \eta_{collector} \times \eta_{P.G.}$$

Although the efficiency of the power generation cycle increases as a function of the cycle peak temperature, the collector efficiency drops significantly because of larger energy losses at higher temperatures. Therefore, a rather flat optimum operating temperature curve exists where the system efficiency is at its peak, in the range of operating temperatures from 280°C to 316°C. The determining factor is the availability of a suitable working fluid and the influence of temperature on the receiver tube coating. Both of these favor the lowest possible temperature consistent with power generation efficiency. A midrange temperature of 295°C was selected as the best compromise.

The daily operating hours were calculated by numerical methods using the diurnal variation in insolation and the incidence factor appropriate to the relative sun position. The three given days were used to construct a curve of annual variation in daily operating hours at 500 kW electrical. This curve is shown in Figure 6. The annual operating time is 2144 hours. Only at the equinox design condition does the system operate entirely from solar insolation. At all other times, the system operates from a combination of storage and solar insolation, using the storage tank as a buffer. The study assumes sufficient storage is available to avoid collector desteering and is only an estimate of system output.

The system estimated performance is listed below. Figure 7 shows the power stair steps and subsystem efficiencies.

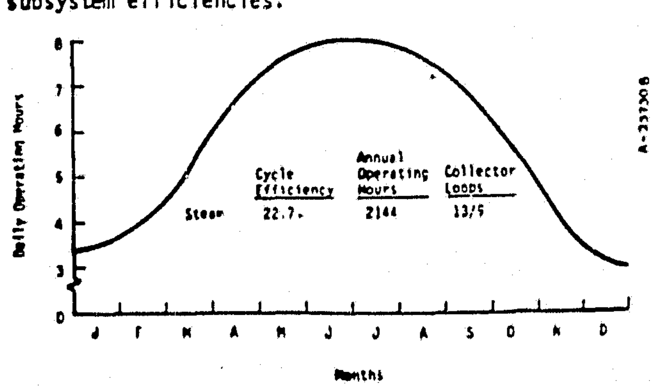

Figure 6. Annual variation in daily operating hours.

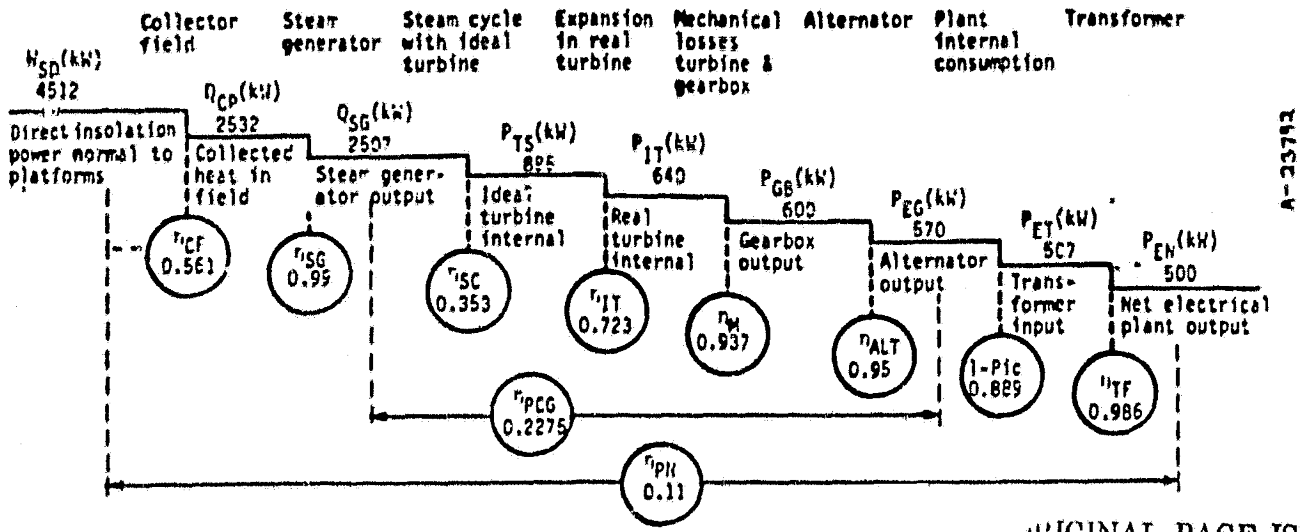

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Figure 7. Power stair steps and efficiencies of the IEA-Solarfarm Almeria.

DESIGN PERFORMANCE

Collector field flow rate	13.8 kg/sec
Collector inlet temperature	225°C
Collector outlet temperature	295°C
Design insolation	920 Watts/m^2 at equinox noon
Minimum operating insolation	300 Watts/m^2
Nominal storage capacity	0.8 MWH
Steam generator outlet conditions	278°C at 25 BAR
Power conversion cycle efficiency	22.75 percent
System overall efficiency	11 percent
Net electrical output	500 KW
Annual operating hours at 500 kWe	2144 HR

Transient Analysis. In consideration of the thermal lag in the collector field, studies were conducted of various strategies for anticipating the lag so that over- or undershoots of outlet temperature can be avoided. Figure 8 shows a case when the insolation drops and is then restored, such as a cloud passage. If only the field outlet temperature is measured there is first a loss in outlet temperature and a cutback in field flowrate and then later a temperature overshoot and steady state error if a slow response control is used. The same thing occurs with a fast response control but outlet temperature oscillations are more pronounced and longer lasting. When the insolation is sensed and used to control the field flowrate, then the initial temperature drop is nearly eliminated but some oscillations in outlet temperature remain. When both the outlet temperature (feedback) and the insolation (feedforward) are sensed, then the system oscillations are better controlled. It has been demonstrated at the USDOE/Sandia Solar Total Energy facility that feedforward alone does not give adequate control, so the feedback element appears essential. The control system for the IEA-SSPS-DCS program incorporates the feedforward-feedback concept. Subsequent analyses of system transient response were calculated on the basis of a feedforward-feedback control strategy.

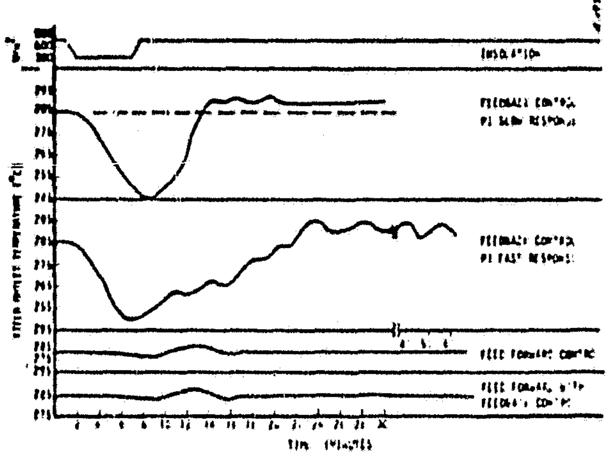

Figure 8. System transient response.

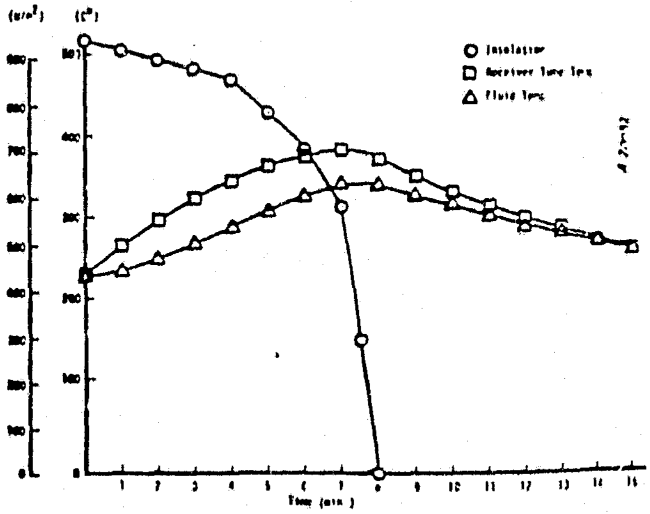

Figure 9. Power loss temperature profiles (while tracking).

A number of transient analyses were conducted in addition to the basic studies described above:

- Transient thermal response of the Acurex collector to a loss of power, Figure 9
- Temperature rise in the Acurex collector receiver during the ten-second startup time of the emergency generator assuming loss of pump power during the transient, Figure 10
- Temperature rise in the Acurex collector receiver for a static collector after loss of tracker power if the sun crosses the focal plane, Figure 11

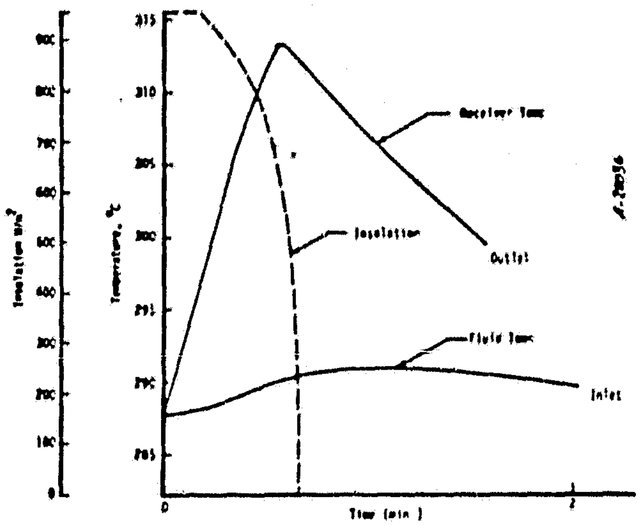

Figure 10. Thermal effect of desteering delayed by 10 seconds.

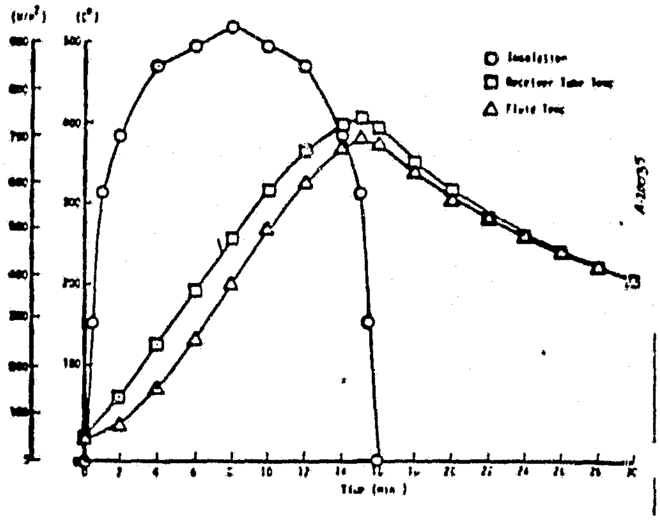

Figure 11. Static collector temperature profiles.

- Analysis of the temperature rise in an Acurex collector field loop when fully shaded after operation at 631 W/m^2 insolation, Figure 12
- Analysis of the inlet and outlet temperature transient for a normal startup procedure for the Acurex fields, Figure 13
- Analysis of the cold startup with 10°C fluid in the thermal storage tank, Figure 14

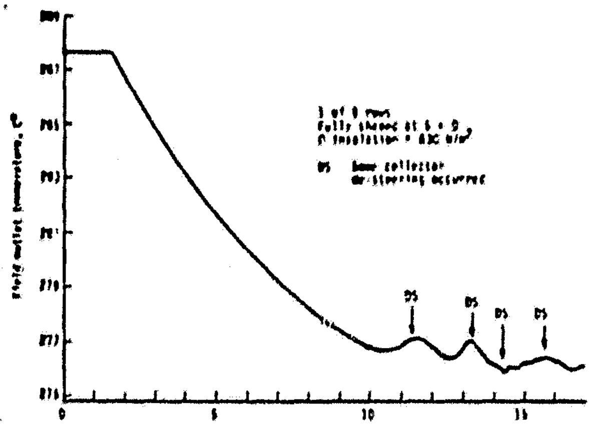

Figure 12. System transient response -- partial cloud cover.

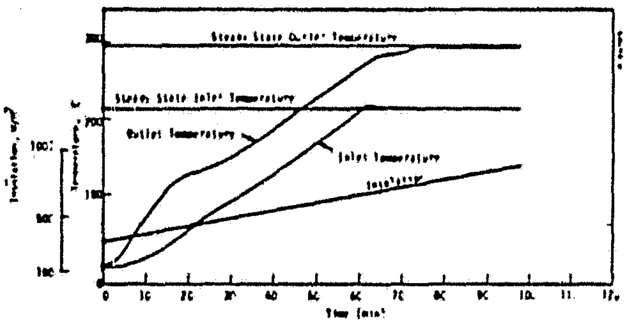

Figure 13. System transient analysis -- normal startup.

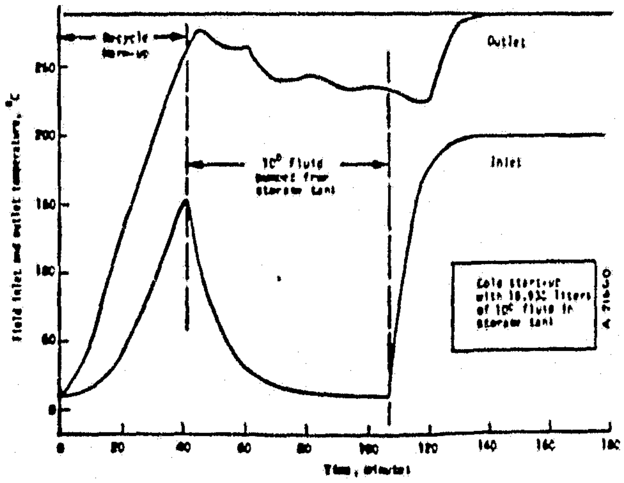

Figure 14. System transient response -- cold startup.

SUMMARY AND CONCLUSIONS

The demonstration plant, when completed in 1981, will provide a working model for use of all participating nations in gathering practical experience in the operation of such systems in both grid-parallel and in stand-alone modes. Extrapolation to larger and smaller systems then can be made from the well established performance at the nominal 500 kW power level.

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