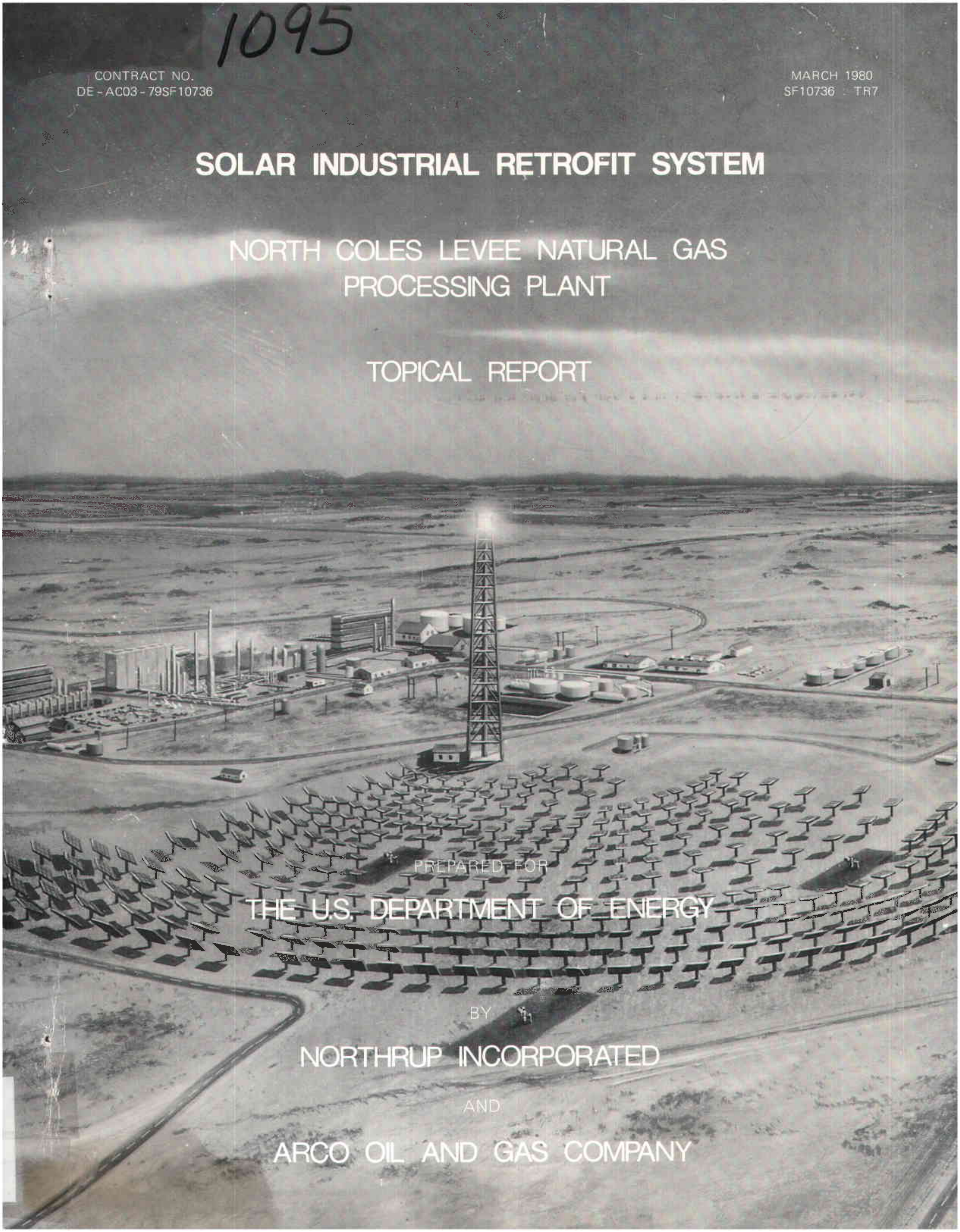
CONTRACT NO.
DE-AC03-79SF10736

MARCH 1980
SF10736 TR7

# SOLAR INDUSTRIAL RETROFIT SYSTEM

## NORTH COLES LEVEE NATURAL GAS PROCESSING PLANT

## TOPICAL REPORT



PREPARED FOR

THE U.S. DEPARTMENT OF ENERGY

BY

NORTHRUP INCORPORATED

AND

ARCO OIL AND GAS COMPANY

March, 1978
SF-10736:TR7

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# 1. INTRODUCTION

This topical report was prepared by Northrup, Inc. to present a summary of the work completed under Department of Energy Contract DE-AC03-79SF10736 of the Solar Repowering/Industrial Retrofit System Program. This project encompasses the conceptual design and evaluation of a solar retrofit system for application in the petrochemical industry. The major efforts, to this point in the contract period, have been to establish the overall system requirements and evaluate subsystems and subsystem components and characteristics upon which a cost effective conceptual system design will be developed.

The design-user team formed to accomplish this project consists of two subsidiaries of Atlantic Richfield Company (ARCO); Northrup, Inc. (NI) as solar system design partner and the ARCO Oil and Gas Company as the industrial user partner.

## 1.1 PROJECT OBJECTIVE

The objective of the program is to develop a site-specific conceptual design of a solar energy retrofit system that will be practical and cost effective in producing process heat for a typical petrochemical industrial application.

## 1.2 APPLICATION DESCRIPTION

The solar powered process heat system is to be installed at the ARCO North Coles Levee Natural Gas Processing Plant No. 8, located 22 miles west of Bakersfield, California.

The plant is a refrigerated absorption oil plant that recovers propane, butane, and gasoline from raw natural gas. The process consists of the raw gas being bubbled through an oil that absorbs the hydrocarbons with molecular chains longer than methane. The process oil is then heated to drive off the absorbed hydrocarbons. These are selectively heated to separate ethane, propane, butane and gasoline. For safety reasons the entire process avoids the direct use of flame and is powered instead by a heat medium oil (HMO) that is heated remotely and circulated to the stripper, deethanizers, depropanizer and debutanizer reboilers. The system operates between 193$^{\circ}$C (380$^{\circ}$F) and 301$^{\circ}$C (575$^{\circ}$F). The process heat is supplied by a combination of two fired heaters and one heat recovery unit that operates on waste heat from a continously operated gas turbine. Nominally, 2.1 million gallons of HMO are circulated through the system daily; 77% of which is heated by the fired heaters. These heaters consume 1.6 x $10^6$ standard cubic feet per day of natural gas.

The solar retrofit system is being designed to provide a heat source for that portion of the HMO that is circulated through the fired heaters; thus directly replacing a portion of the natural gas fuel requirements.

The general arrangement shows a 35-acre array of 320 heliostats occupying a circular sector that has 304.8m (1000 ft.) radius and an included angle of 120$^{\circ}$. It lies due north of a single cavity receiver positioned at the center of curvature, atop a 4-legged steel tower that will place the center of the target plane 200 feet above the ground surface. Figure 1.1 presents an artist's rendition of the collector field layout relative to the plant. The view is from the north "looking" south.

The collector used as a basis for the conceptual design is a second generation heliostat. Each heliostat contains 53.51 m$^2$ (576 ft.$^2$) of reflective surface.

Direct current stepper motors are used to provide drivepower and maintain position accuracy. The field is controlled by a two-level open-loop system.

The receiver loop interfaces with the existing HMO system between the plant pump discharge and the fired heaters. A flow diagram of the process, HMO and solar system interface is shown in Figure 1. 2. During periods of sufficient insolation, the entire HMO that normally flows to the fired heaters is diverted through the receiver and back to the heaters. The heaters then "top-off" the heat required to maintain their outlet temperature of 301$^{o}$C (575$^{o}$F). Fuel flow to the heaters is automatically controlled to supply only enough heat to meet the $\Delta$T requirement, or carry the entire plant load during periods of insufficient insolation. This method of interfacing the solar and non-solar HMO system offers several advantages: (a) All solar energy collected is used; (b) All heat supplied by heat recovery units is used; (c) Fired heaters are maintained at operating temperature and can respond rapidly to transient conditions; (d) System control is extremely simple; and (e) Minimum interruption of existing plant operation.

The solar system is sized to deliver 9,518 kW to the plant at noon, summer solstice. This supplies all the energy that is required, by that portion of the plant powered by the HMO, over and above energy that is available and would be wasted if replaced by solar energy. On this basis solar supplies 33% of the plant annual energy requirement and functions at an average effeciency of 58.2%.

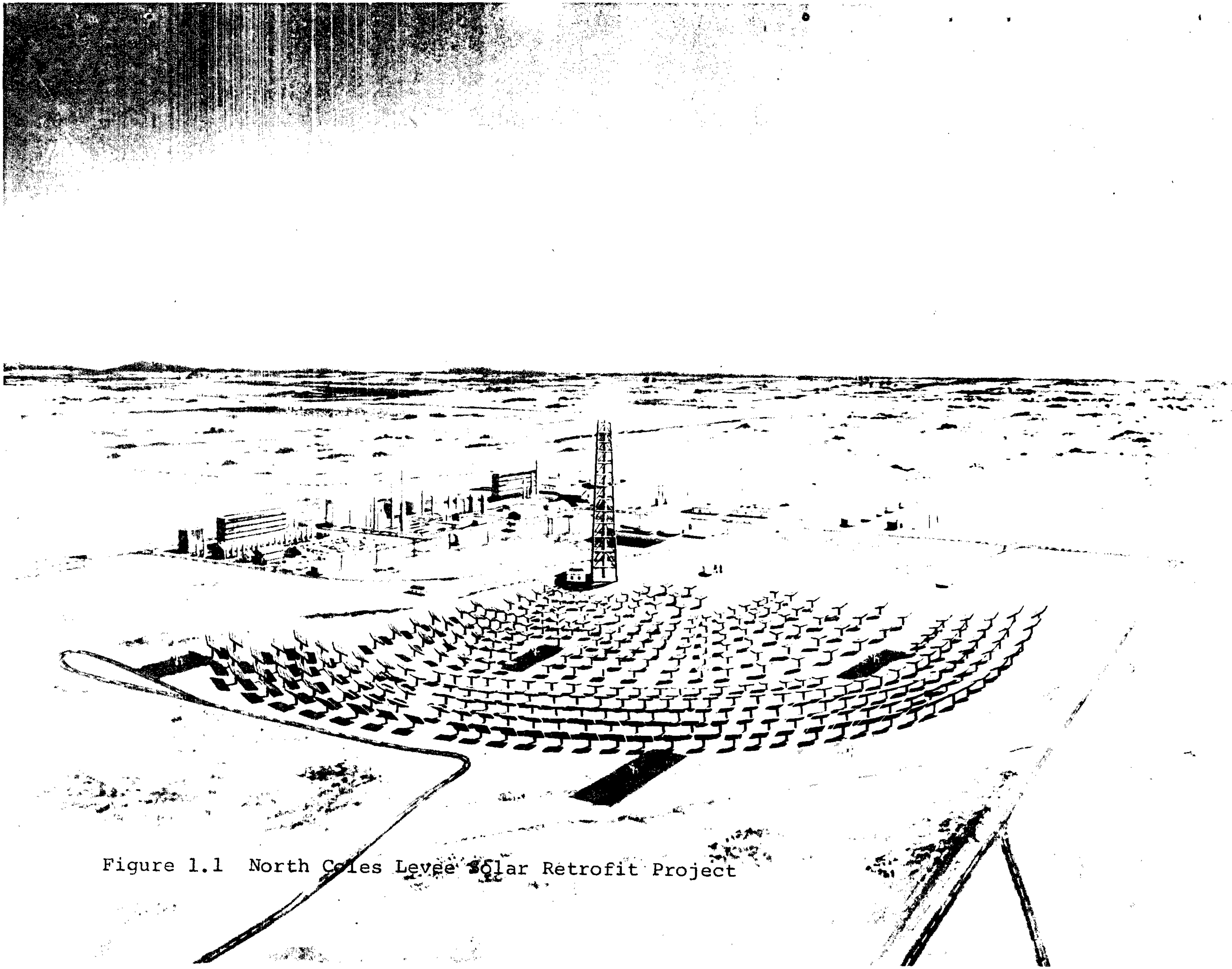


Figure 1.1 North Coles Levee Solar Retrofit Project

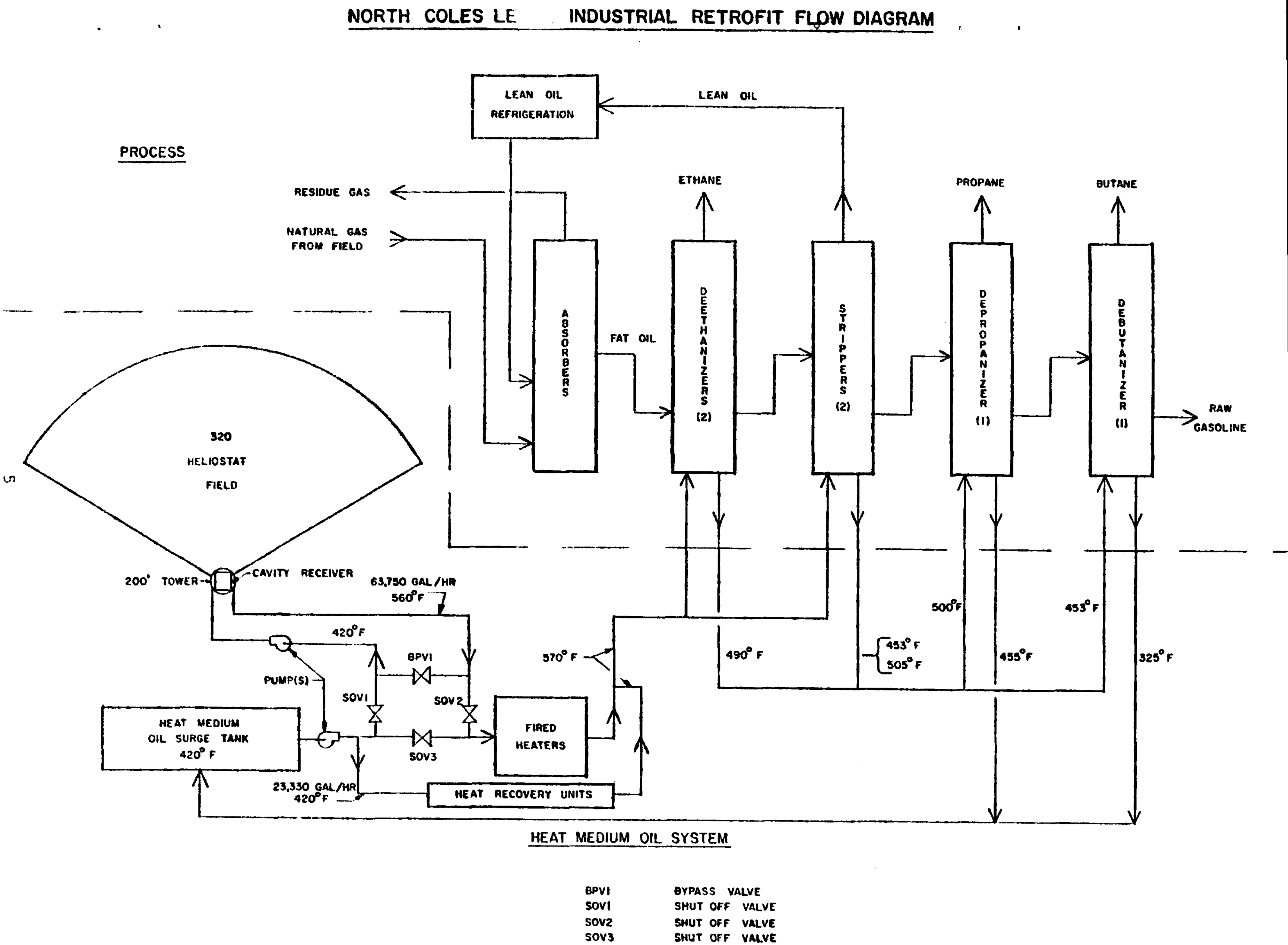



Figure 1.2 North Cole Levee Industrial Retrofit Flow Diagram

ALE

## 2. SUBSYTEM EVALUATION AND SELECTION

In order to develop the most efficient system for minimum cost and within land use and other site-specific constraints, it has been necessary to perform both system and subsystem parametric analyses and trade-studies. These included collector field configurations, receiver types, control strategies, heat augmentation temperatures, and site interfaces.

### 2.1 COLLECTOR SYSTEM

The key parametric analysis involved the evaluation and subsequent selection of a collector field configuration that would be economical, provide maximum collection efficiency and remain compatable with the site specific constraints imposed by an operating oil and gas field. The system design discussed in the proposal was based on a field composed of 23 modules, triangular in shape, each containing 19 heliostats focused on a ground level (towerless) receiver. The primary considerations were the savings due to the elimination of tower costs and the land use versatility and flexibility so important in retrofit applications. However, other central receiver tower modules and radial stagger flat field collector configurations were evaluated to establish the optimum.

2.1.1 Heliostats - The baseline heliostat selected as the basis of the North Coles Levee system design is the Northrup II. This heliostat is being developed under Department of Energy funding for second generation heliostats. Prototype testing is scheduled to be completed the latter part of 1980 and production and delivery can be scheduled to meet the requirements of the North Coles Levee project.

The heliostat is being designed to meet or exceed the structural and performance requirements of specification A10772. The basic configuration is a square array of mirror facets with a total area of 53.51 $m^2$ (576 $ft.^2$) and a specular reflectivity of 0.87.

2.1.2 Heliostat Control - The heliostat control system is also being developed as a part of the work under the second generation heliostat development program. Here again, the tracking, slewing, and positioning capabilities will meet the requirements of specification A10772. However, complete control is derived from an open-loop, two-level (Array Controller & Heliostat Controller) system. Actual positioning is accomplished by stepper motors and calculated position based on step count rather than AC or DC motors with encoder position monitoring. Baseline position knowledge is derived from limit switches at the ends of travel.

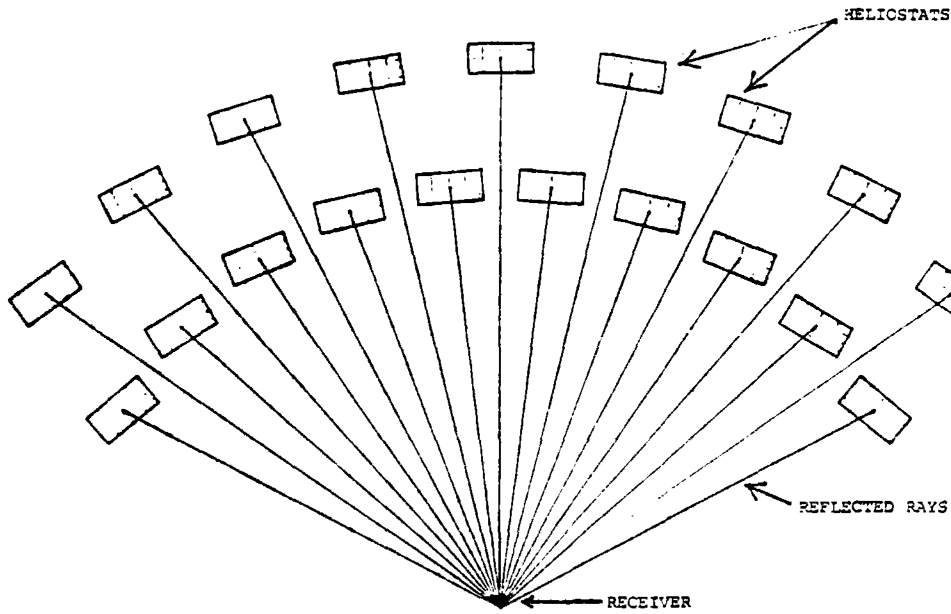
2.1.3 Field Configuration - The selection of a suitable collector field configuration was the major thrust under this task. The 23 module towerless field configuration presented in the proposal utilized a triangular (two straight row) module arrangement composed of 19 heliostats each (Figure 2.1 ). Since this field configuration offered unique advantages (elimination of tower cost and land use flexibility) in retrofit situations, the initial effort was to determine if performance could be improved by placing the heliostats in a radial stagger configuration (Figure 2.1 ).

Evaluation and final selection between these two towerless fields was based on annual performance and land use considerations. Table 2.1 presents the performance comparison between the two configurations. The radial stagger module exhibits a higher peak performance while the triangular module shows a higher annual performance. This annual performance advantage is less than 0.5%.

RADIAL STAGGER FLAT FIELD LAYOUT

216 FT OUTER. ROW, 166.5 FT INNER ROW

RADIAL LAYOUT NO. 3 FOR 19 - 53.51 M² HELIOSTATS




TRIANGULAR FLAT FIELD LAYOUT

224.8 FT OUTER ROW, 175.3 FT INNER ROW

LAYOUT NO. 8 FOR 19 - 53.51 M² HELIOSTATS

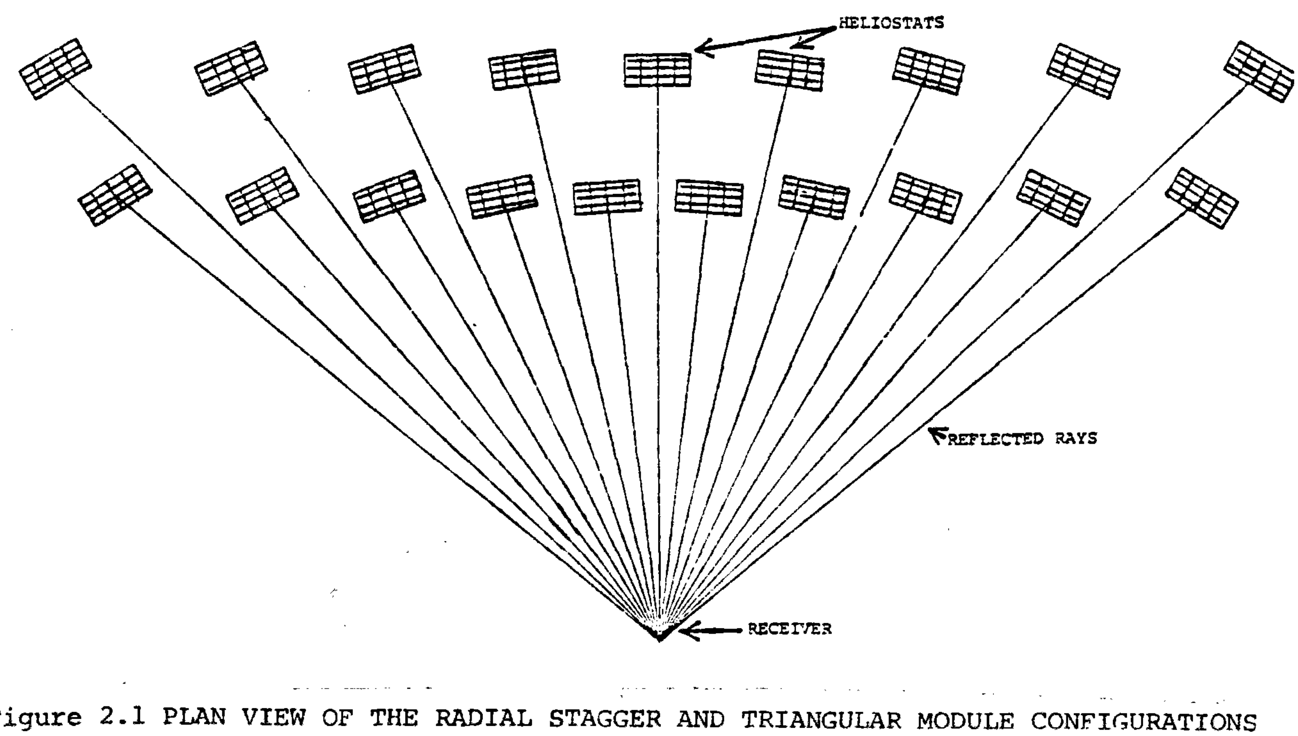





Figure 2.1 PLAN VIEW OF THE RADIAL STAGGER AND TRIANGULAR MODULE CONFIGURATIONS

TABLE 2.1

TOWERLESS MODULE EVALUATION

Straight Rows vs. Radial Stagger Rows

| PARAMETER | STRAIGHT ROW - TRIANGULAR | RADIAL STAGGER ROW - SECTOR |
|---|---|---|
| I. PHYSICAL COMPARISON | | |
| 1.1 No. of Heliostats per Module | 19 | 19 |
| 1.2 Mirror Area | 53.51 $m^2$ (576 $ft^2$) | 53.51$m^2$ (576 $ft^2$) |
| 1.3 Module Size | | |
| 1.3.1 Width, E-W | 143m (469 ft) | 108m (353 ft) |
| 1.3.2 Depth, N-S | 68m (225 ft) | 66m (216 ft) |
| 1.3.3 Area | 9803$m^2$ (105,512 $ft^2$) | 7094$m^2$ (76,356 $ft^2$) |
| 1.4 Packing Density | .0873 | .1207 |
| II. PERFORMANCE COMPARISON | | |
| 2.1 Peak Geometric Efficiency | .9084 | .9239 |
| 2.2 Annual Geometric Efficiency | .7672 | .7639 |
| 2.3 Annual Energy (19 Heliostats) | $3.468 \times 10^7$ | $3.457 \times 10^7$ |
| 2.4 Peak Energy | 734 MW | 740 MW |
| 2.5 Peak Flux | 230 $KW/m^2$ | 240 $Kw/m^2$ |

Table 2.1 also presents the physical comparison between the two modular configurations. The significance of this comparison is the much smaller land requirements of the radial stagger configuration. The triangular module requires about 10% more land area than does the radial stagger module.

Since land use is an important consideration in field layout, and annual performance is not significantly different, the radial stagger configuration was selected as the baseline flat field modular configuration for the remainder of the field selection effort.

After selection of the towerless module configuration, a cost/performance evaluation was conducted for four heliostat field configurations to provide a basis for selection of the collector field to be used in the conceptual design. These were of the modular field type and included the 23 module towerless field, the quad (4) module field, the dual (2) module field, and the unit or single module field. The 23 unit, quad, dual and unit module field configurations are shown in plan in Figures 2.2, 2.3, 2.4 and 2.5. As shown in the figures, all field layouts except the unit configuration are shown with extra modules. This was done to facilitate the selection of the best module placement considering the existing gas, oil and injection wells; pipe lines; and electrical and communication lines.

The collector field performance for each field configuration was evaluated by computer, which required the determination of the coordinates of the heliostats and the sun position as input. The code uses this information to calculate the cosine factors, shading, and blocking for each heliostat in the collector field. These values are averaged over the field reflector area and, combined with the tower shadow, produce an overall geometric performance efficiency matrix for 36 sun positions. The field performance is calculated by combining the hourly isolation data with the appropriate geometric performance, obtained from interpolation of the efficiency matrix and based on sun position, and summed

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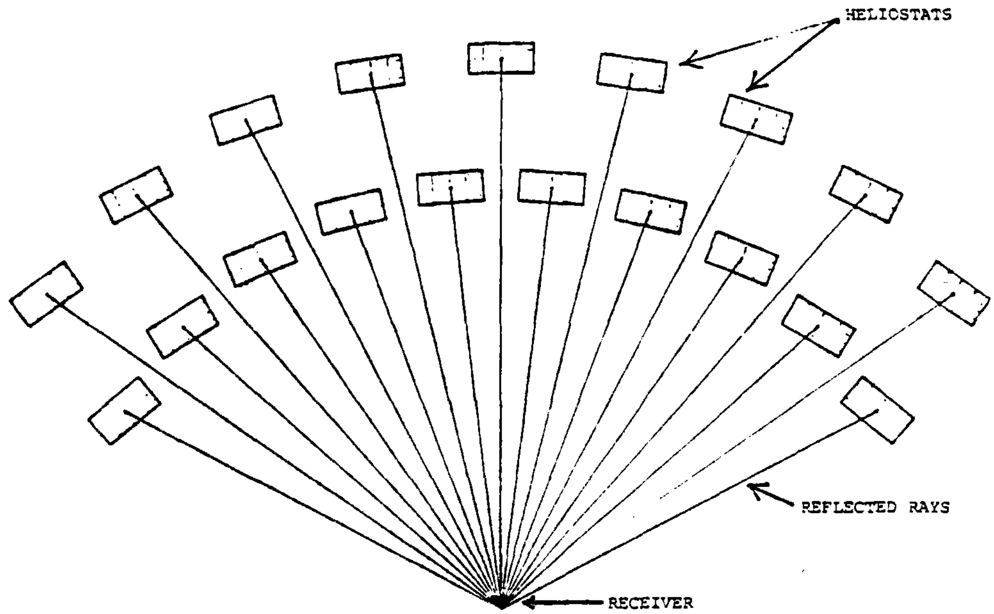
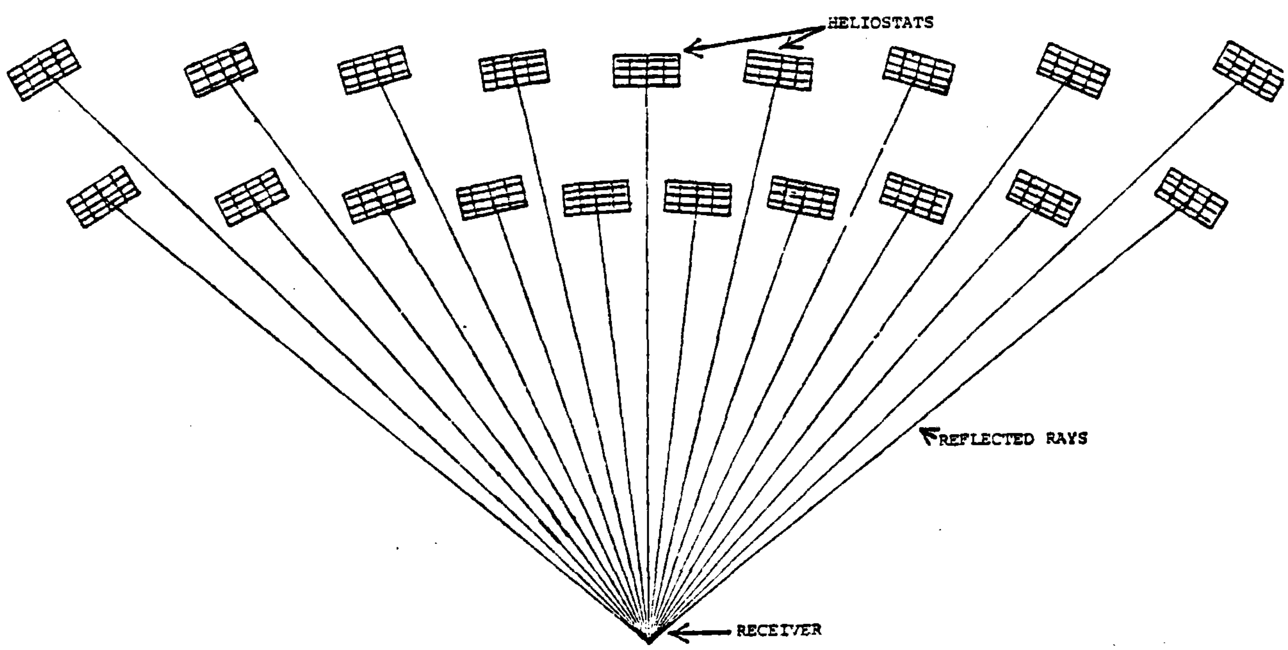



## TRIANGULAR FLAT FIELD LAYOUT

224.8 FT OUTER ROW, 175.3 FT INNER ROW

LAYOUT NO. 8 FOR 19 - 53.51 M² HELIOSTATS



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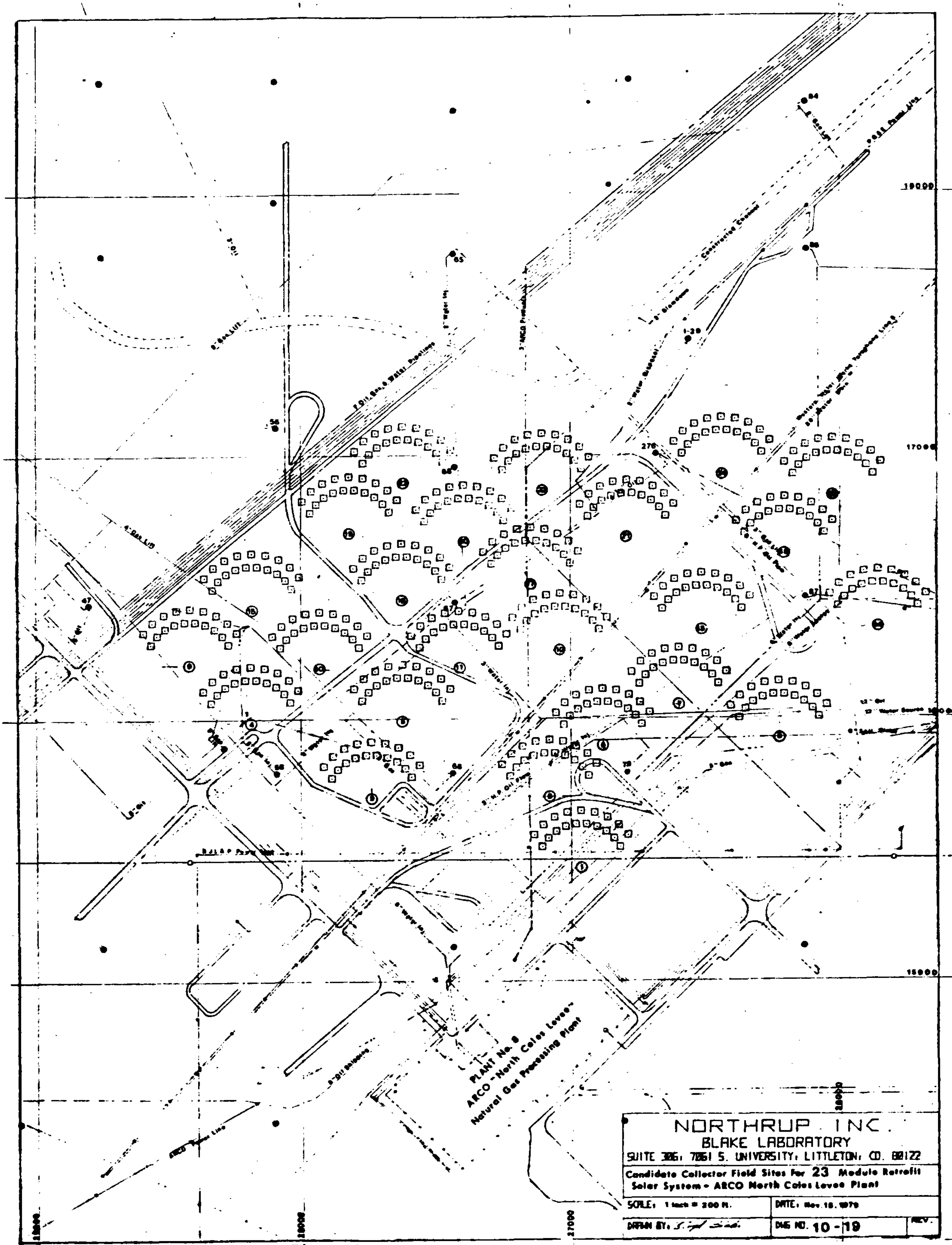

NORTHRUP INC.
BLAKE LABORATORY
SUITE 306, 7061 S. UNIVERSITY, LITTLETON, CO. 80122
Candidate Collector Field Sites For 23 Module Retrofit Solar System - ARCO North Coles Levee Plant
SCALE: 1 inch = 200 ft.
DWG NO. 10 - 19
REV.
PLANT No. 8
ARCO "North Coles Levee"
Natural Gas Processing Plant

Figure 2.2

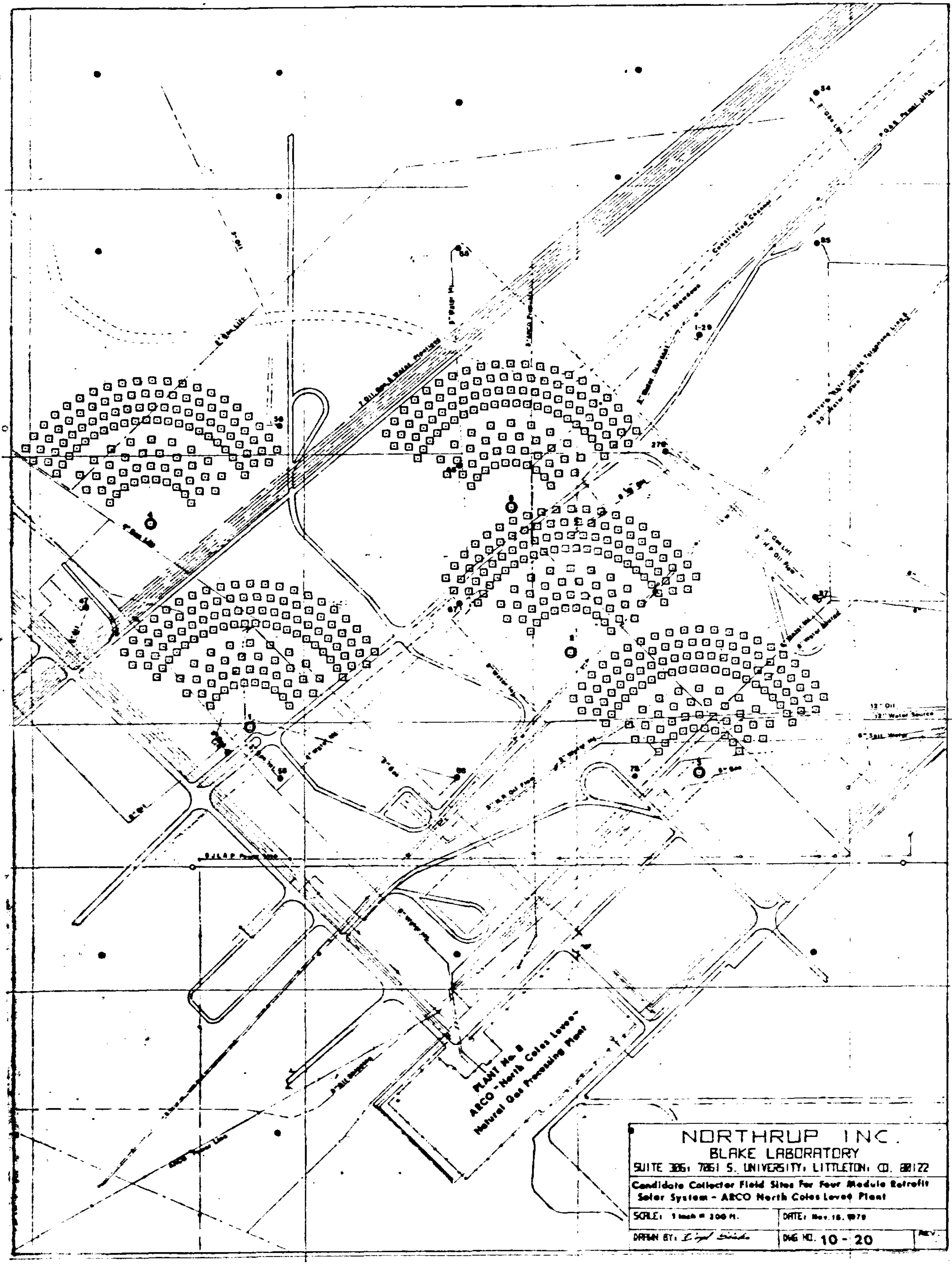

PLANT No. 8
ARCO - North Coles Levee -
Natural Gas Processing Plant
NORTHRUP INC.
BLAKE LABORATORY
Candidate Collector Field Sites For Four Module Retrofit
Solar System - ARCO North Coles Levee Plant
SCALE: 1 inch = 200 ft.
DATE: Nov. 16, 1979
DRAWN BY:
DWG NO. 10 - 20
REV.

Figure 2.3

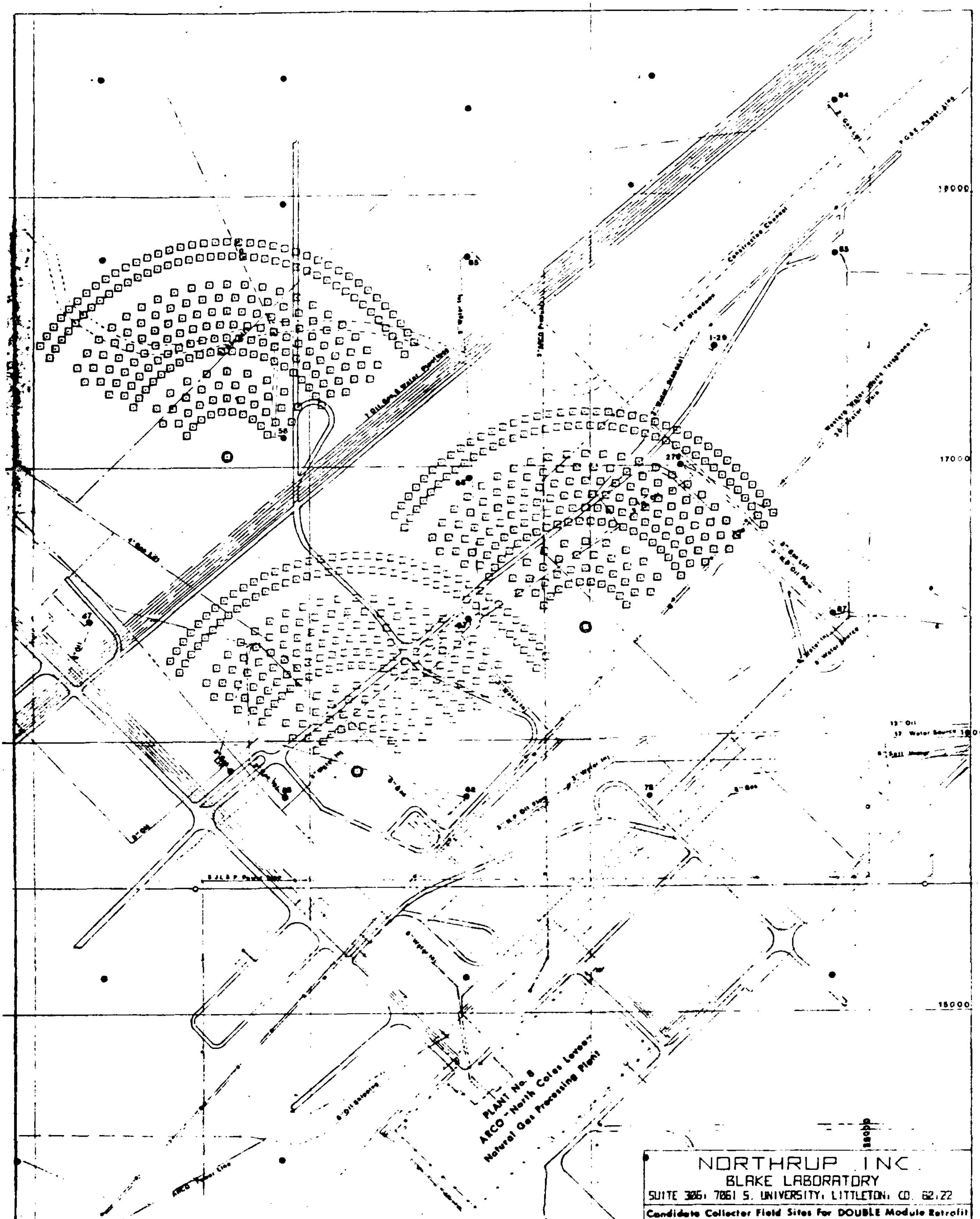

NORTHRUP INC.
BLAKE LABORATORY
SUITE 306, 7061 S. UNIVERSITY, LITTLETON, CO. 80122
Candidate Collector Field Sites For DOUBLE Module Retrofit
Solar System - ARCO North Coles Levee Plant
SCALE: 1 inch = 200 ft.
DATE: Nov. 15, 1978
DRAWN BY:
DWG NO. 10 - 21
REV.
PLANT No. 8
ARCO - North Coles Levee
Natural Gas Processing Plant
18000
17000
16000
15000
28000
27000

Figure 2.4

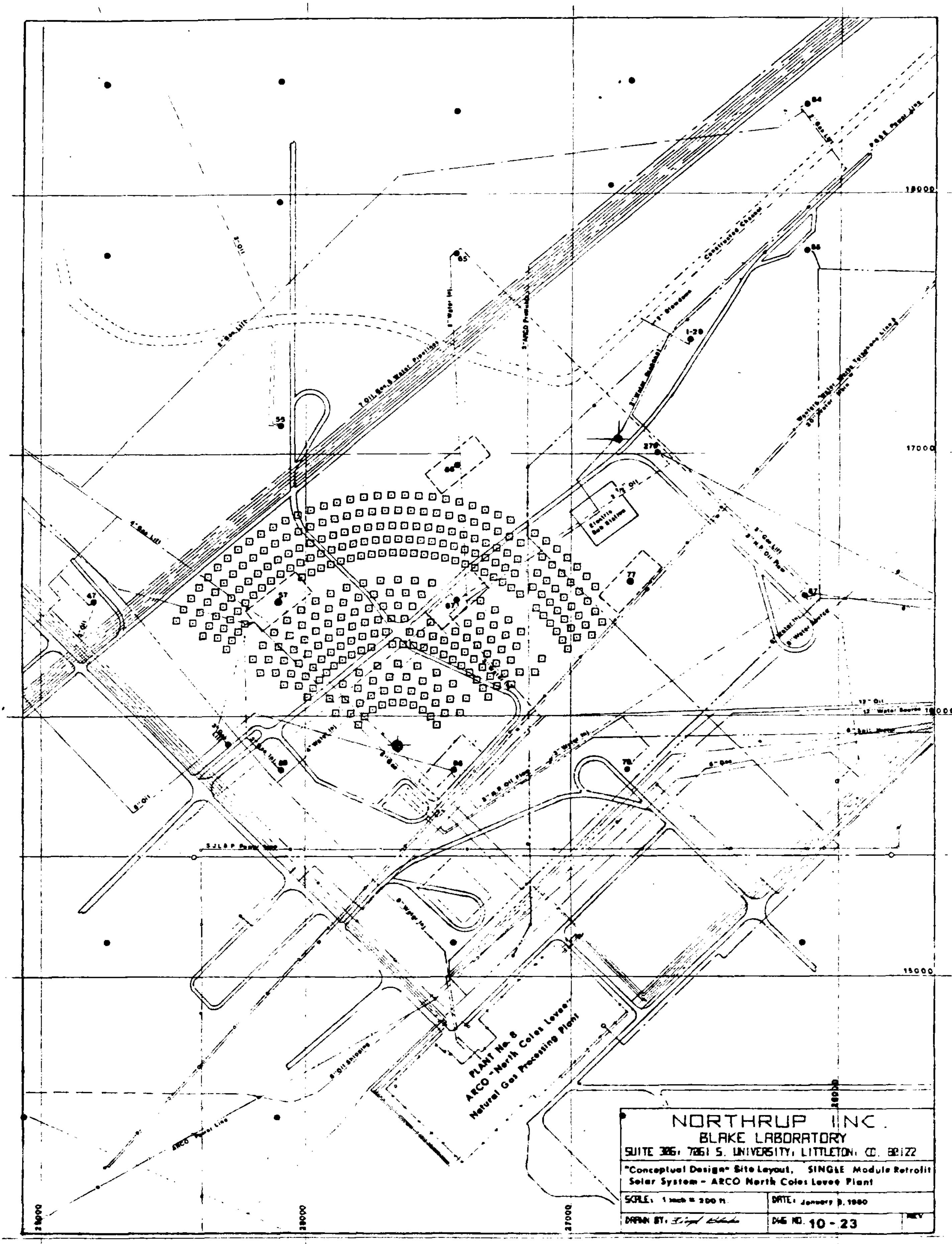

NORTHRUP INC.
BLAKE LABORATORY
SUITE 306, 7061 S. UNIVERSITY, LITTLETON, CO. 80122
"Conceptual Design" Site Layout, SINGLE Module Retrofit Solar System - ARCO North Coles Levee Plant
SCALE: 1 inch = 200 ft.
DATE: January 8, 1980
DRAWN BY:
DWG NO. 10 - 23
REV
PLANT No. 8
ARCO "North Coles Levee"
Natural Gas Processing Plant
18000
17000
16000
15000
27000
SJL&P Power Line
ARCO Power Line
Electric Sub Station



Figure 2.5.

over the entire year. Since the atmospheric attenuation does not vary significantly over the range of field dimensions, it was only considered in calculations of the annual energy collected.

To compare the cost of the four solar collector subsystem configurations, it is necessary to normalize the costs for performance variations. The collector subsystems and tower costs were analyzed by use of the algorithm:

$$C_{CN} = \frac{C_H + C_T + C_R + C_W}{\eta} + C_P$$

where:

$C_{CN}$ = the normalized collector subsystem cost

$C_H$ = installed cost of heliostats

$C_T$ = tower cost

$C_R$ = receiver cost

$C_W$ = field wiring cost

$C_P$ = piping cost

$\eta$ = field efficiency

The input and variations of the terms of the algorithm were defined as follows:

* Heliostats costs ($C_H$) were established by placing the results of all performance calculations on the basis of a field size of 437 heliostats; each containing 53.51 $m^2$, reflective surface area. An installed cost of \$230.0 per $m^2$, recommended in Reference 1, was used in the calculation.
* The tower costs ($C_T$) were calculated using the SLL steel tower cost algorithm recommended in Reference 1 and are presented in Table 2.2.
* The receiver costs ($C_R$) were based on using flat plate design for the towerless field and adapting a scaled up version of this receiver to develop the single cavity configuration for the tower receivers.

## TABLE 2.2

### STEEL TOWER COST
(Dollars-1978)

| FIELD CONFIGURATION | TOWER HEIGHT | RECEIVER WEIGHT | TOWER COST | FOUNDATION COST | ACCESSORY COST | ENG.& FEE | TOTAL (1 TOWER) |
|---|---|---|---|---|---|---|---|
| SINGLE | 200 ft. | 48,000 | 73,525 | 210,358 | 215,000 | 124,720 | 623,606 |
| DUAL | 174 ft. | 23,520 | 52,815 | 182,591 | 209,800 | 111,301 | 556,507 |
| QUAD | 135 ft. | 12,000 | 37,288 | 164,854 | 202,000 | 101,000 | 505.178 |

* The wiring costs ($C_W$) were estimated from the requirements of supplying each heliostat 115 VAC drive power and control signals.

* Piping costs ($C_P$) were estimated from visually optimized layouts superimposed on each field, and include the riser and downcomer.

* The field efficiency ($\eta$) is the integrated average of the geometric efficiency taken hourly from 6 a.m. to 6 p.m. for the year 1976 at Barstow, Ca., for times when the isolation was above 500 $W/m^2$.

A complete cost and performance comparison is presented in Table 2.3.

Other considerations included; (1) operations and maintenance costs should not differ significantly between the field configurations, (2) piping losses would be minimum for the single module, and (3) the single tower module is more efficient relative to the total land utilization.

As a result of the evaluation of the above data, Northrup has selected the single module field for the design of North Coles Levee solar process heat system.

The design point that has been established (Section 3.1) is for the solar system to deliver to the heat medium oil system at the plant interface, 9.518 $kW_t$ at noon on the summer solstice. This design point is based on less energy production than originally proposed and as a result, the collector field has been re-sized to meet the revised requirement. The most recent calculations showed that a field size of 320 heliostats would be adequate to meet this design requirement.

2.2 RECEIVER SYSTEM - The receiver system consists of the receiver proper, tower, and riser/downcomer pipes. The original concept incorporated modules that contained receivers near ground level, hence no towers were required. Based on subsequent analyses, the field configuration has been revised to a single collector array with the receiver positioned at an optical height of 61 m (200 ft.) above ground level. The system design has therefore been expanded to include the tower and riser/downcomer piping.

TABLE 2.3

SOLAR INDUSTRIAL RETROFIT SYSTEM
NORTH COLES LEVEE PROJECT

COLLECTOR FIELD SELECTION EVALUATION DATA

| SELECTION CRITERIA | 23 MODULE "FLAT" FIELD (Proposal) | QUAD MODULE TOWER FIELD (Towers-135') | DUAL MODULE TOWER FIELD (Towers-174') | SINGLE MODULE TOWER FIELD (Tower-200') |
|---|---|---|---|---|
| I. COST (1979 Dollars) | | | | |
| 1.A HELIOSTATS | 5,378,500 | 5,378,500 | 5,378,500 | 5,378,500 |
| 1.B TOWERS | -0- | 2,020,712 | 1,113,016 | 623,603 |
| 1.C RECEIVERS | 344,712 | 179,506 | 213,698 | 188,054 |
| 1.D PIPING | 495,364 | 301,587 | 164,005 | 81,698 |
| 1.E WIRING | 29,179 | 33,731 | 28,706 | 27,817 |
| TOTAL | 6,247,750 | 7,914,036 | 6,897,925 | 6,299,671 |
| II. ACTUAL PERFORMANCE | | | | |
| 2.A ANNUAL EFFICIENCY | 0.763899 | 0.83312 | 0.83144 | 0.829824 |
| 2.B ANNUAL ENERGY TO RECEIVER (Kw/Hr) | 3.457 (7) | 3.762 (7) | 3.754 (7) | 3.7422 (7) |
| III. RELATIVE EVALUATION | | | | |
| 3.A NORMALIZED COST $\left\{\frac{\text{Cost}}{\text{Efficiency}}\right\}$ | 8,178,771 | 9,499,264 | 8,296,359 | 7,591,575 |
| 3.B SPECIFIC CAPITAL COST ($/Kw Hr) | .18073 | .21036 | .18373 | .16834 |
| IV. EFFECTIVE RELATIVE COST (Single Tower Basis) | 1.07735 | 1.2496 | 1.0914 | 1.000 |

Prior to the final field selection for this project, the conceptual design of a flat-plate type ground-level receiver had been developed. It is possible that a pilot project or other retrofit projects with severe land use constraints will dictate a return to the smaller towerless collector module. Also, it is conceivable that this receiver will be used in the pilot unit for this project. A description of this receiver was presented in the October Monthly Report (TPR-2) and will be included as an appendix to the final report.

2.2.1 Receiver Subsystem - As a result of the selection of a field configuration using a tall tower 61 m (200 ft.) an appropriate receiver is being designed. The receiver will be a north-facing cavity type. The flow rate through the receiver has been established at 63,750 gal/hr of heat medium oil. The normal operating range will be 215.5$^{o}$ to 293$^{o}$C (420$^{o}$F to 560$^{o}$F). The receiver is being sized to deliver 9,518 $MW_t$ at the point of interface with the existing plant system.

In general, the receiver geometry will be a circular arc segment; 120$^{o}$ included angle on a 7.3 m (24 ft.) radius; approximately 10 m (39 ft.) in height; with the aperture centerline 61 m (200 ft.) above ground level. The conceptual design and analysis is currently in progress.

Initial work has included the optimization of the size of the receiver aperture. The optimization is based on the combined efficiencies of four fundamental properties of a receiver; the spillage, the absorptivity, the radiation and convection. The efficiencies were calculated for winter and summer solstices and spring equinox for three aperture sizes. The results of these calculations are tabulated in Table 2.4. The results show that the 6.4 x 6.4 m (21 ft x 21 ft) aperture provides the overall highest efficiency.

TABLE 2.4

RECEIVER APERTURE OPTIMIZATION

| DAY NO. | APERTURE (FT) | SPILLAGE | ABSORPTIVITY | RADIATION | CONVECTION | COMBINATION |
|---|---|---|---|---|---|---|
| 80 | 27 x 27 | .9907 | .9787 | .9756 | .9258 | .8758 |
| 80 | 21 x 21 | .9698 | .9777 | .9849 | .9541 | .8910 |
| 80 | 15 x 15 | .8716 | .9769 | .9915 | .9740 | .8222 |
| | | | | | | |
| 173 | 27 x 27 | .9850 | .9787 | .9734 | .9190 | .8624 |
| 173 | 21 x 21 | .9506 | .9777 | .9833 | .9492 | .8675 |
| 173 | 15 x 15 | .8204 | .9767 | .9902 | .9701 | .7699 |
| | | | | | | |
| 355 | 27 x 27 | .9932 | .9787 | .9766 | .9288 | .8818 |
| 355 | 21 x 21 | .9776 | .9777 | .9854 | .9562 | .9008 |
| 355 | 15 x 15 | .8948 | .9769 | .9920 | .9756 | .8460 |

2.2.2 Receiver Surface Analysis - During the design of the receiver for the "towerless" field module, an analysis related to the utilization of selective surface vs. black paint was conducted. The analysis demonstrated that for the ground level receivers, the problem is really one of selective surface availability; if selective surface finish is available which can withstand the thermal environment (204°C - 371°C) it should be used on this type receiver. The benefit of a selective surface vs. a non-selective, black painted surface will produce a system performance improvement of about 5%. The radiation problem is less critical for the cavity receiver and black paint will suffice. Analysis are continuing.

2.2.3 Tower - The tower design has only recently been initiated as a result of the single module field configuration selection. Initial costs estimates used in the field selection were based on using a four legged steel tower and the cost algorithms recommended by SLL. More detailed tower design and evaluation and selection is in progress.

## 2.3 SOLAR/FOSSIL INTERFACE

The interface between the solar system and the existing HMO system includes several areas. The most prominent of these are the interface of the receiver fluid loop with the heat medium oil system and the collector field interface with the available land.

2.3.1 Heat Medium Oil System Interface - The interface of the existing plant heat medium oil system with the solar system has been evaluated. Three points were selected for analysis. Thses are shown schematically in Figure 2.6. In all cases the oil flows through the fired heaters in the usual manner.

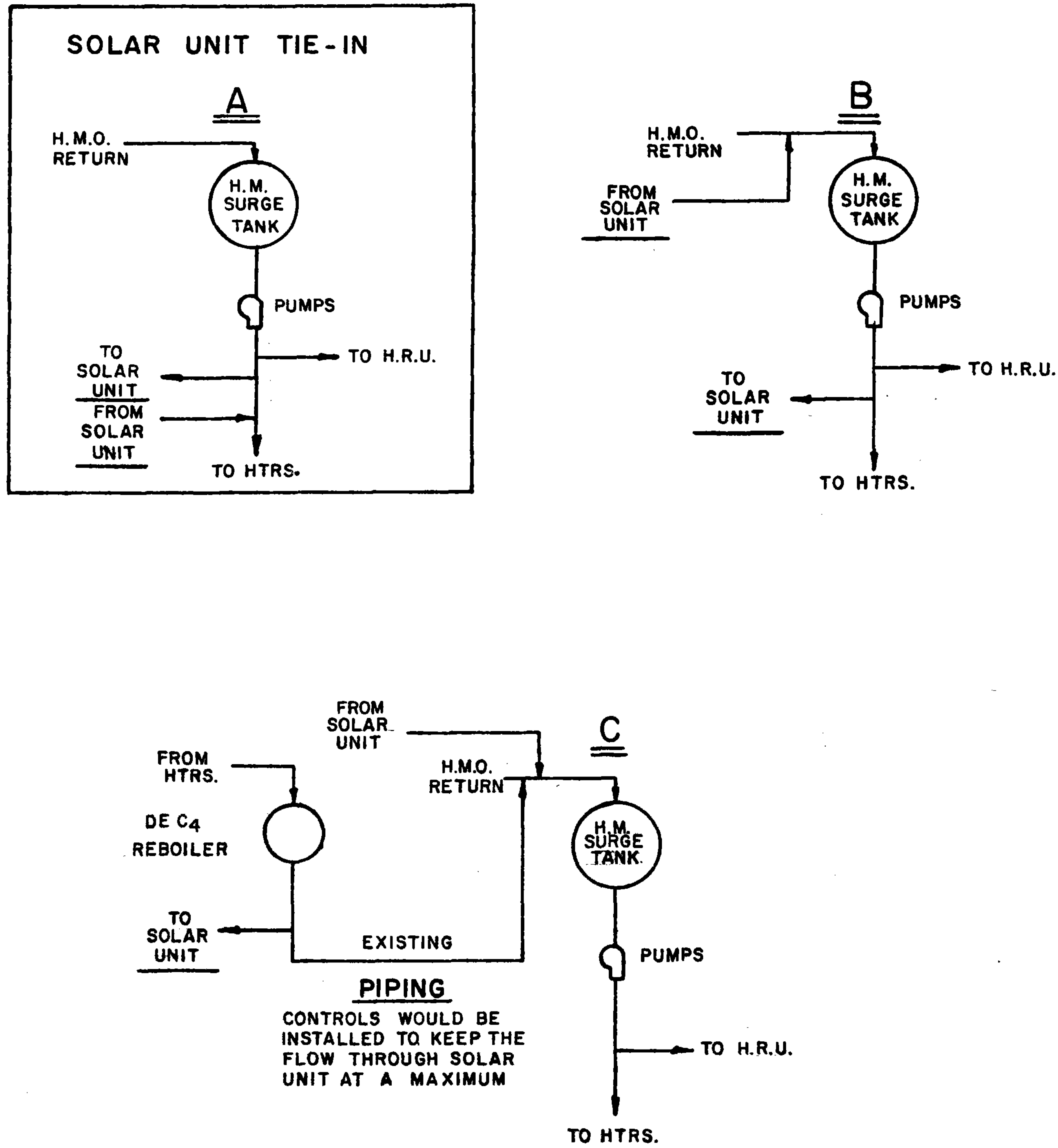



**Figure** 2.6 Candidate Heat Medium Oil Interface Connections

The hook-up shown in schematic C would provide the maximum $\Delta T$ across the solar system because the heat medium outlet from the debutanizer is the lowest in the system (approximately 320$^{O}$F). Unfortunately, this process requires less than 5% of the heat produced by the fired heaters.

The hook-up shown in schematic B would permit a much larger flow through the solar system but would raise the temperature in the heat medium surge tank, thereby reducing the $\Delta T$ across the solar system. Also, the HMO system pumps would be required to operate at much higher temperatures.

Schematic A shows the interface selected. Here all the heat medium oil that flows through the fired heaters would be routed through the solar system (after the solar system oil has been brought up to the average surge tank operating temperature - approximately 215.5$^{O}$C, 420$^{O}$F) and return to the inlet of the fired heaters which will raise the temperature to the required 570$^{O}$F. Solar would supply all heat collected until the input to the fired heaters dropped below the surge tank temperature. At this time the solar system would be blocked out and the plant would return to normal operation. The maximum solar return temperature would be limited to approximately 560$^{O}$F. This is necessary because the fired heaters cannot be completely extinguished during solar operation. The remaining $\Delta T$ of 5.6$^{O}$C (10$^{O}$F) will be furnished by the heaters operating at minimum level.

This method of interfacing the solar and non-solar HMO systems offer several advantages:

1. All solar energy collected is used.
2. All heat supplied by heat recovery units is used.
3. Fired heaters are maintained at operating temperature and can respond rapidly to transient conditions.
4. System control is extremely simple.
5. Minimum interruption of existing plant operations.

2.3.2 Collector Field Installation - The site proposed for the collector field is relatively flat and level and is clear of major obstructions. However, it is a producing oil and gas field and, as such, contains numerous oil and gas wells, with associated transport and injection pipelines and unimproved access roads. There is also a telephone and power line and a 30 in. water main that traverse portions of the field, Figure 2.5. The well sites require an unobstructed area 30.5 m (100 ft) x 73.2 m (240 ft) for placement of workover platforms and redrilling equipment when that type of well maintenance is required. These restrictions were not considered of sufficient severity to prohibit installation. Once the collector field configuration had been selected and sized, it was possible to analyze the placement to minimize both the interference with oil field operations and collector field integrity. Figure 2.5 shows a plan view of the final field placement. In this position only two wells fall within the field perimeter and one well pad intersects the outer row of heliostats on the extreme eastern edge. All power and telephone lines and the 30 in. water main lie outside. Other small pipelines still remain within the field. Minor position adjustments to a small number of heliostats should adequately eliminate any interference with those existing lines. With the construction of two short access roads and relocation of a materials storage area, the collector field installation should be completely compatable with the existing land use plan.

## 3. CONCEPTUAL DESIGN

### 3.1 SOLAR SYSTEM PERFORMANCE REQUIREMENTS

The heat medium oil (HMO) system is illustrated in the temperature/flow diagram in Figure 3.1 Total daily HMO circulation through the system averages 2,100,000 gal. The system capacity is approximately 20,000 gal., divided almost evenly between the surge tank (10,000 gal.) and the piping system. The system level is maintained at approximately 18,000 gal. which requires that each segment of the fluid circulate through the system 117 times each day.

There are various inlet and outlet temperatures maintained at the several processes by system by-pass valves and loops. All HMO outlets from the process reheaters and reboilers return to the surge tank, which remains at an average temperature of 216$^{o}$C (420$^{o}$F). The HMO is pumped from the surge tank to a Nordberg Heat Recovery Unit (HRU) and two natural gas fired heaters where each of these units raises the HMO temperature to 305$^{o}$C (575$^{o}$F). The 2.1 x $10^{6}$ gal./day flow rate combined with the T of 68.3$^{o}$C (155$^{o}$F) results in a calculated energy production of 4.94 x $10^{7}$ Btu/hr or 1.45 x $10^{4}$ KWt.

Of this total energy production, approximately 33% is furnished by the HRU which utilizes the heat rejected from the one 5500 hp Nordberg Gas Turbine that is used as prime mover for the compressor used in a water flood project. This rejected heat is available 24 hrs per day and would be wasted if not utilized in the heat medium system. For this reason, this energy was not considered as replacable by solar as no fossil fuel displacement would result.

The flow rate through the HRU averages 560,000 gal. per day. This flow, combined with the 68.3$^{o}$C$\Delta$T produces 1.31 x $10^{7}$ Btu/hr or 3.858 x $10^{3}$ KWt.

The remainder, 3.631 x $10^{7}$ Btu/hr or 1.06 x $10^{4}$ KWt is delivered to the system by the fired heaters.

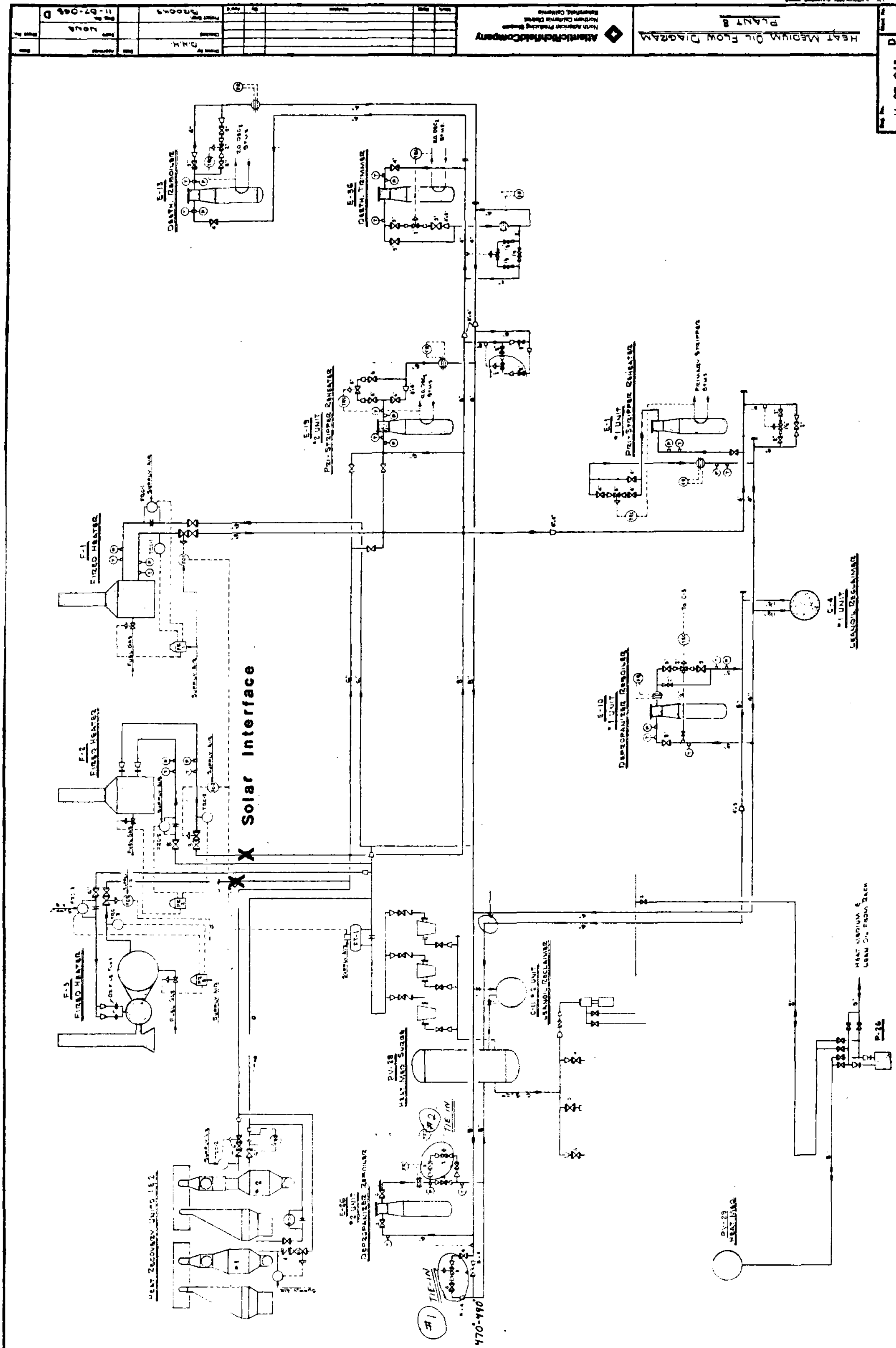



Figure 3,1

There is an additional limitation on the amount of energy to be supplied by the solar system. The heat supplied by the fired heaters is controlled relative to system demand by control of fuel gas to the heater burners. Adequate control is accomplished quite easily and automatically, within the narrow limits of the normal operating range, by a TRC valve in the fuel line which is controlled by the HMO outlet temperature. However, complete start-up from a cold or complete fuel shut-off condition is a somewhat complicated and lengthy process involving safety systems, alarm systems, flame provers, pilot burners, torch lighters and main burners. In order to eliminate the daily (or even more often in the case of cloud transients) burner shut-down and start-up process or a complete redesign of the existing control system, it was decided that the heaters would remain in service, but operating at a maximum turndown of 10 to 1. In order that the remaining heat not be wasted during periods of high solar insulation, the decision was made to design the solar system such that the constant flow of HMO through the heaters would be retained and the solar system sized to return the HMO to the system at a maximum temperature that would still allow the fired heaters operating at maximum turndown level to utilize the energy produced to "top-off" the HMO to meet the 301$^{o}$C (575$^{o}$F) process temperature requirement. This design criteria will greatly simplify the control system and minimize installation and operational interference with routine plant operations while remaining compatible with the existing safety system and associated procedures.

In order to fully utilize the energy produced when the fossil system is operating at minimum, the solar system was sized to supply sufficient energy to increase the HMO temperature from 216 C (420 F) to 293 C (560 F) and return it to the inlet of the fired heaters where the temperature is increased to the required 301C (575 F).

Based on the above, a system rating value has been established for solar system sizing and design as follows:

| | | | |
|---|---|---|---|
| 2,100,00 | Gal./Day | heat medium flow for plant |
| -570,000 | " | to heat recovery unit |
| 1,530,000 | | to fired heaters |

flow rate = 63,750 Gal./ Hr.

$T = 560^{\circ} F - 420^{\circ}F = 140^{\circ}F$

Specific Heat = .60 Btu/lb. $^{\circ}F$

Specific Gravity = .731

Heat Requirement = $32.49 \times 10^{6}$ BTU/Hr.

= 9,518 KWT

3.2 RECEIVER

With the energy requirements of the solar system established and the flux distributions incident upon the receiver calculated, the actual design began. The analysis work is being done using the Northrup Arcoles Receiver Analyzer computer program. The criteria established to define the philosophy as well as the parameters that govern the operational limits of the receiver systems are presented on page 28..

The receiver design incorporates standard size Platecoil panels produced by the Tratner Manufacturing Co. (Figure 3.2) The panels are available in a wide variety of metals, sizes, flow patterns, manifold connections, pass sizes and embossing patterns.

The Arcoles Analyzer was used to evaluate the system parameters for a number of panel sizes, physical arrangements, and flow patterns to establish an **optimum** balance and efficiency within the above design criteria.

TABLE 3.1 RECEIVER DESIGN CRITERIA

* USE COMMERCIALLY AVAILABLE STANDARD HARDWARE TO THE MAXIMUM EXTENT POSSIBLE.

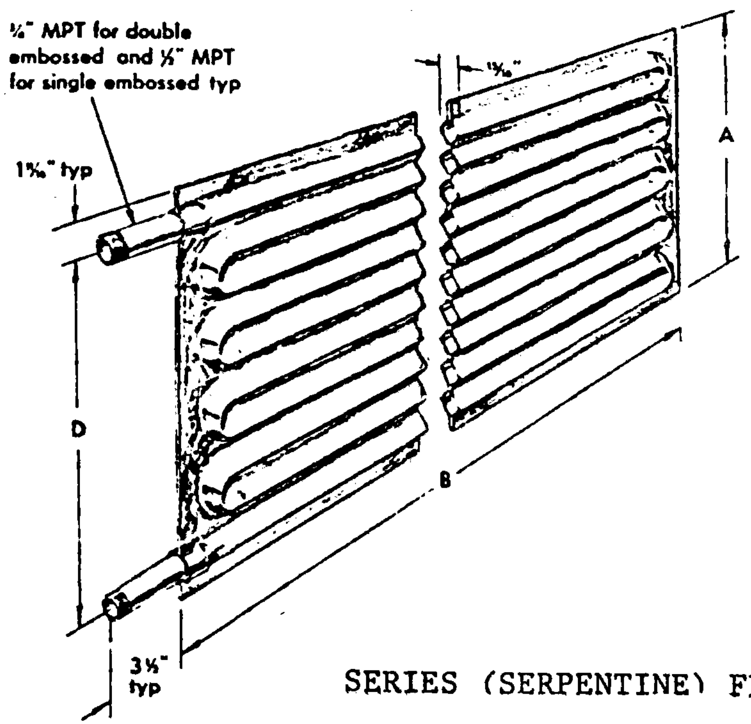
* USE LOW COST CARBON STEEL PANELS, PIPE, AND FITTINGS. AVOID STAINLESS STEEL AND SUPER ALLOYS.

* MINIMIZE THE USE OF CONTROL VALVES, PUMPS, AND OTHER "ACTIVE" COMPONENTS.

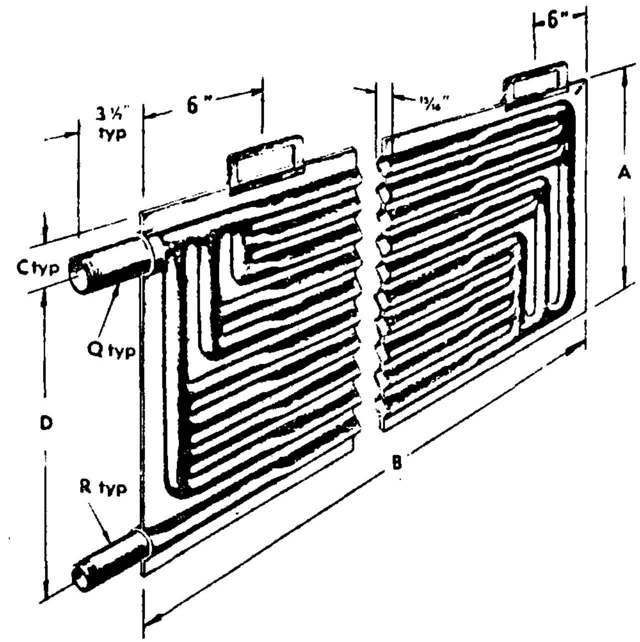
* DESIGN FOR MINIMUM METAL AND OIL TEMPERATURES AND MINIMUM RECEIVER PRESSURE LOSS:

   1. LIMIT PEAK OIL TEMPERATURE TO 600°F.
   2. LIMIT PEAK TUBE WALL TEMPERATURE TO 650°F.
   3. LIMIT PEAK NON-WETTED METAL TEMPERATURE TO 675°F.
   4. LIMIT RECEIVER PRESSURE LOSS TO 50 PSI.
   5. LIMIT PEAK THERMAL STRESS TO 25,000 PSI.

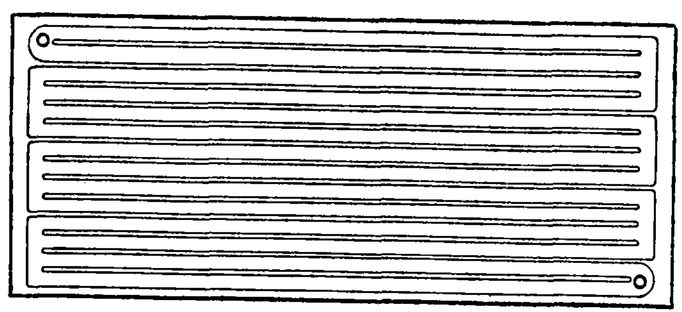
FIGURE 3.2 SERIES VS PARALLEL FLOW OPTION




SERIES (SERPENTINE) FLOW




PARALLEL FLOW



SERIES-PARALLEL FLOW

The receiver model used for the calculations was composed of 52 plate coil panels; three stacked rows of 14 each and 10 horizonal or cross-panels for return bend protection (Figure 3.3). The flow pattern was established to be a series/parallel arrangement - basically parallel through each row and surpentine through each panel. The Platecoil panel selected is shown in figure 3.5. Flow rates and associated pressure losses relative to each panel were calculated. The pressure drop results are shown in figure 3.6.

For the heat transfer analysis, each of the vertical panels was divided into three modal zones and each cross panel remained a single zone for a total of 136 zones. The assumptions used in the transfer analysis are summarized in figure 3.7. The basis for the panel fin and wet-wall network analysis is shown in figure 3.8. Combining these inputs with the receiver configuration previously described, the Arcoles Analyzer then characterized each modal zone and summed the results over the entire receiver. A sample computer printout for a typical zone is shown in figure 3.9.

A summary of the results for the selected receiver is as follows:

* MAXIMUM FIN TEMPERATURE 659$^{O}$F
* MAXIMUM TUBE TEMPERATURE 628$^{O}$F
* MAXIMUM OIL TEMPERATURE 600$^{O}$F
* MAXIMUM THERMAL STRESS 21.484 PSI

The receiver energy balances and efficiencies are summarized in Table 3.1.

3.3 CONTROL SYSTEM:

The controls at each heliostat will consist of two stepper motor drive electronics and the microprocessor controls to interface with the

FIGURE 3.3 RECEIVER DIMENSIONS AND PANEL ORIENTATION

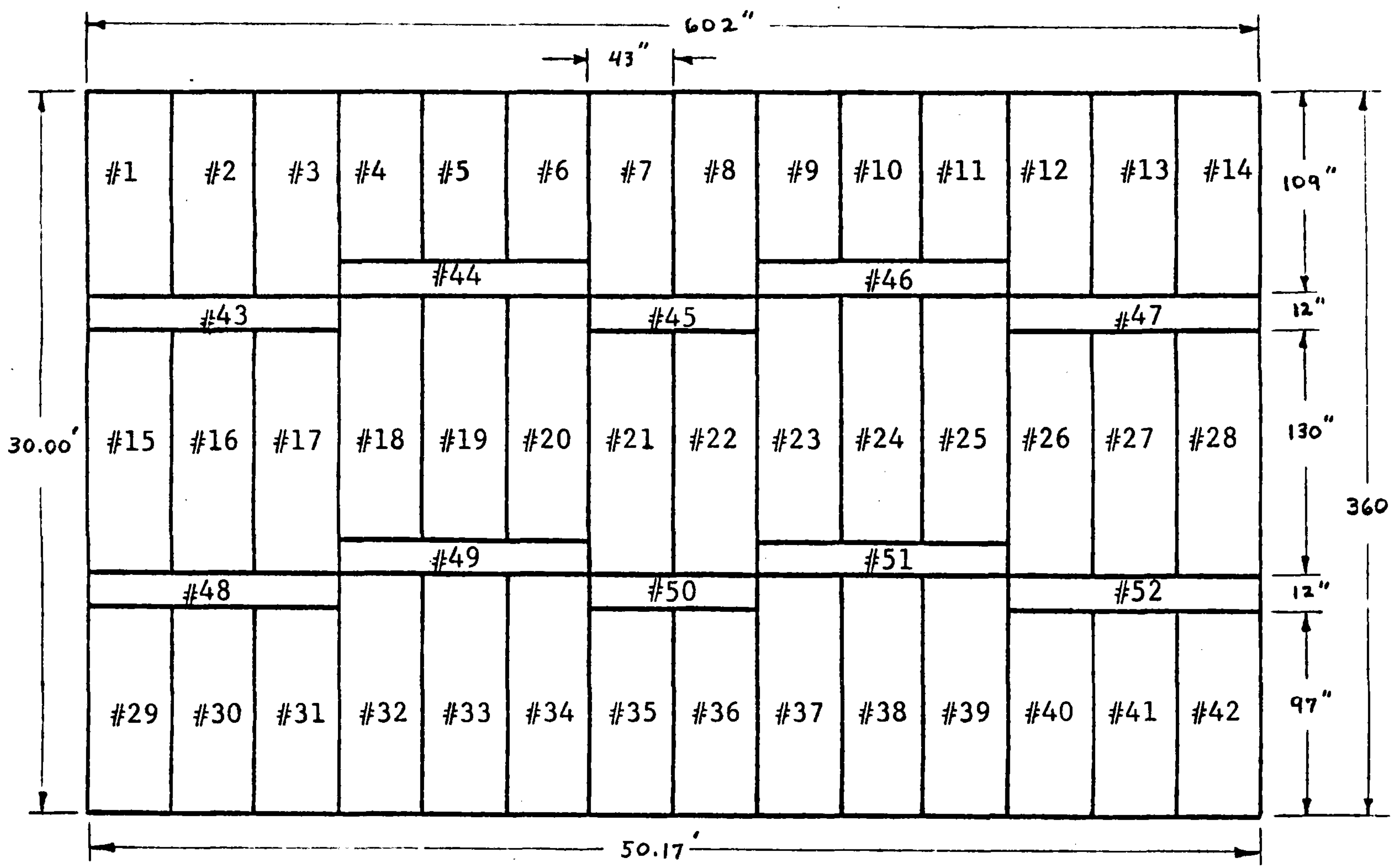


FIGURE 3.4 RECEIVER FLOW PATH & FLOW DISTRIBUTION

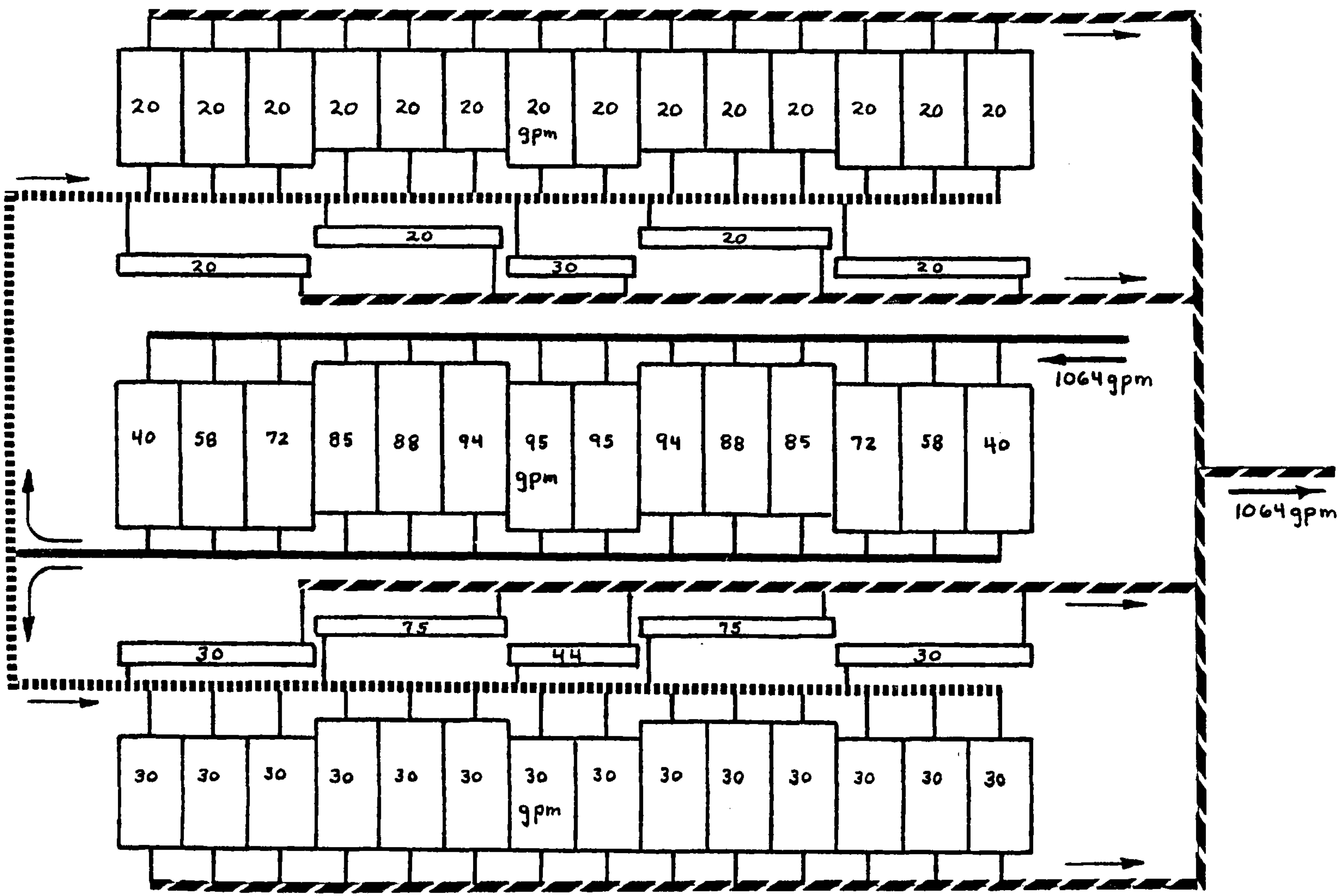
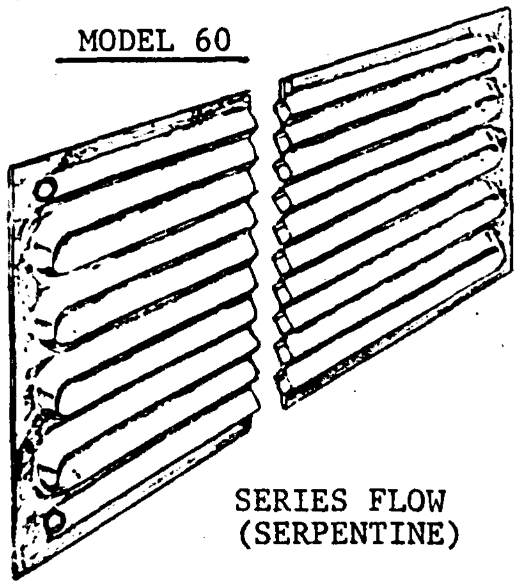
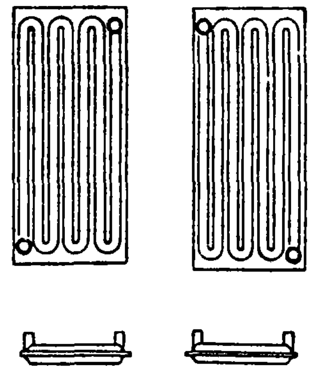


FIGURE 3.5 SELECTED PLATECOIL CONFIGURATION

MODEL 60

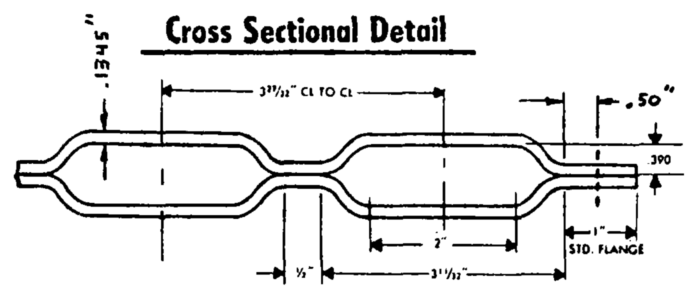


SERIES FLOW (SERPENTINE)




DOUBLE EMBOSSED

**Cross Sectional Detail**




Internal Cross Sectional Area: Double embossed 2.1 sq. in.

**Width vs Number of Passes**

| No. of Passes | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Actual Width | $5\frac{3}{8}$ | $9\frac{3}{16}$ | 13 ✓ | $16\frac{7}{8}$ | $20\frac{3}{4}$ | $24\frac{9}{16}$ | $28\frac{3}{8}$ | $32\frac{1}{4}$ | $36\frac{1}{8}$ | $39\frac{15}{16}$ | $43\frac{3}{4}$ ✓ |

Furnished as standard in the following lengths:

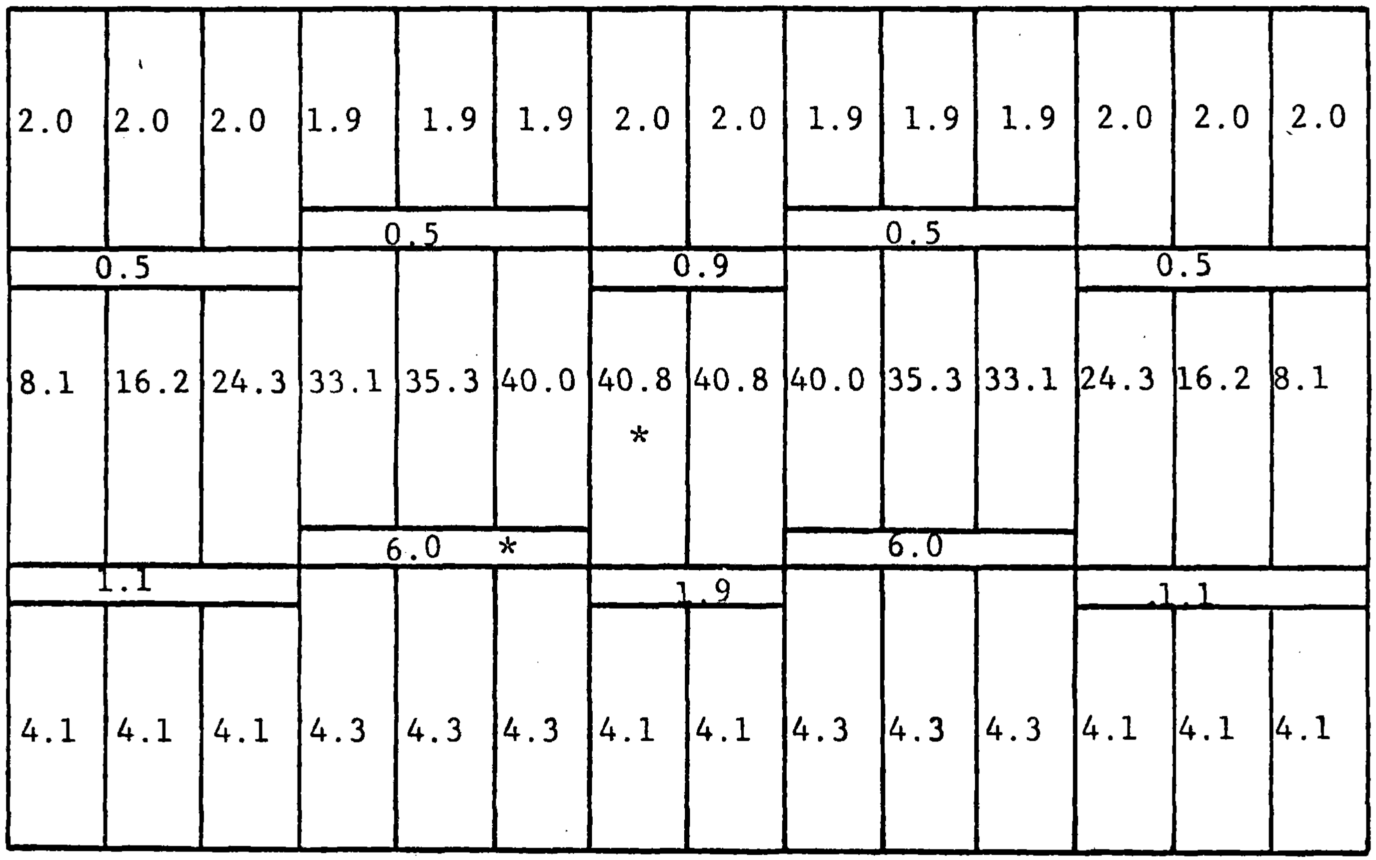
| | | |
|---|---|---|
| 23" | 59" | 107" ✓ |
| 29" | 71" | 119" ✓ |
| 35" | 83" | 131" |
| 47" | 95" | 143" ✓ |

**OPERATING PRESSURES CARBON✓AND 300 SERIES STAINLESS STEEL AND MONEL ASME AND STANDARD**

| GA. | DOUBLE EMBOSSED | SINGLE EMBOSSED COMPANION PLATE (GA.) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 16 | 14 | 12 | 11 | 10 | 9 | 8 | 3/16 | 1/4 | 5/16 | 3/8 |
| 16 | 25 | 10 | 20 | 30 | 40 | 50 | 60 | 65 | 70 | 70 | 70 | 70 |
| 14 | 30 | | 20 | 30 | 40 | 50 | 60 | 70 | 90 | 90 | 90 | 90 |
| 12 | 60 | | | 40 | 50 | 70 | 70 | 80 | 110 | 110 | 110 | 110 |
| 11 | 80 | | | | 50 | 80 | 80 | 90 | 120 | 120 | 120 | 120 |
| 10 ✓ | 120 | | | | | 90 | 90 | 100 | 130 | 130 | 130 | 130 |

| QTY | SIZE | PASS | FITTING |
|---|---|---|---|
| 7 | 43"x143" | 11 | L.H. |
| 7 | 43"x143" | 11 | R.H. |
| 7 | 43"x119" | 11 | L.H. |
| 7 | 43"x119" | 11 | R.H. |
| 7 | 43"x107" | 11 | L.H. |
| 7 | 43"x107" | 11 | R.H. |
| 2 | 13"x107" | 3 | L.H. |
| 8 | 13"x143" | 3 | R.H. |

FIGURE 3.6 RECEIVER PANEL PRESSURE LOSSES, $\Delta P$, PSI

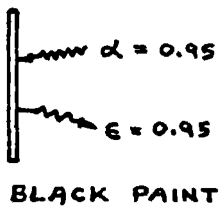



* These series panels dictate total receiver pressure loss = 46.8 psi

Assuming 70% motor-pump efficiency, pump power = 30.7 KW

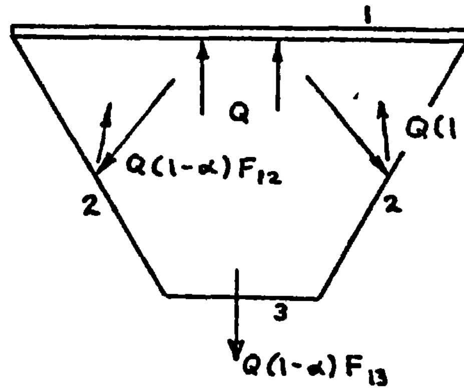
FIGURE 3.7 HEAT TRANSFER ANALYSIS - ASSUMPTIONS

## SURFACE PROPERTIES



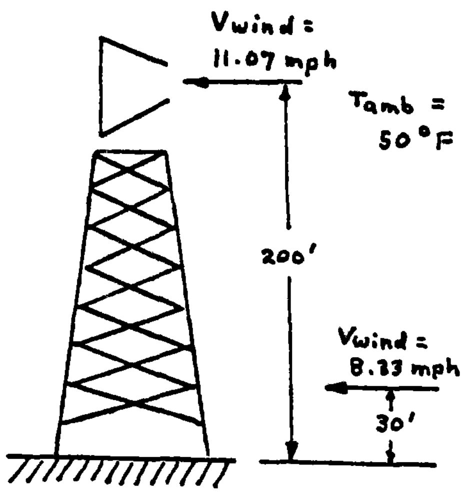

Assumption: Non-Selective black paint with moderate optical properties.

## ABSORPTIVITY LOSSES

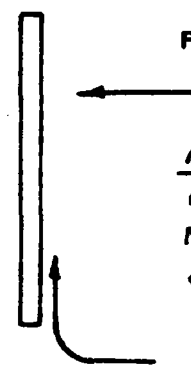



Assumption: 50% of the reflected energy striking the cavity walls is absorbed by those walls.

## WEATHER




## CONVECTION LOSSES



Forced Convection:

$$h = 0.931 (\rho c_p V_\infty) Re^{-1/2} Pr^{-2/3} \ *$$

Assumption: Receiver panels are exposed to the full wind velocity. Natural and forced convection effects are additive.

Natural Convection:

$h = 1.0$ BTU/ft$^2$-hr-°F

* Sparrow & Tien, Journal of Heat Transfer, Nov. 1977, Vol 99, pg. 507-512.

figure 3.8 DETAILED FIN & WET-WALL NETWORK ANALYSIS

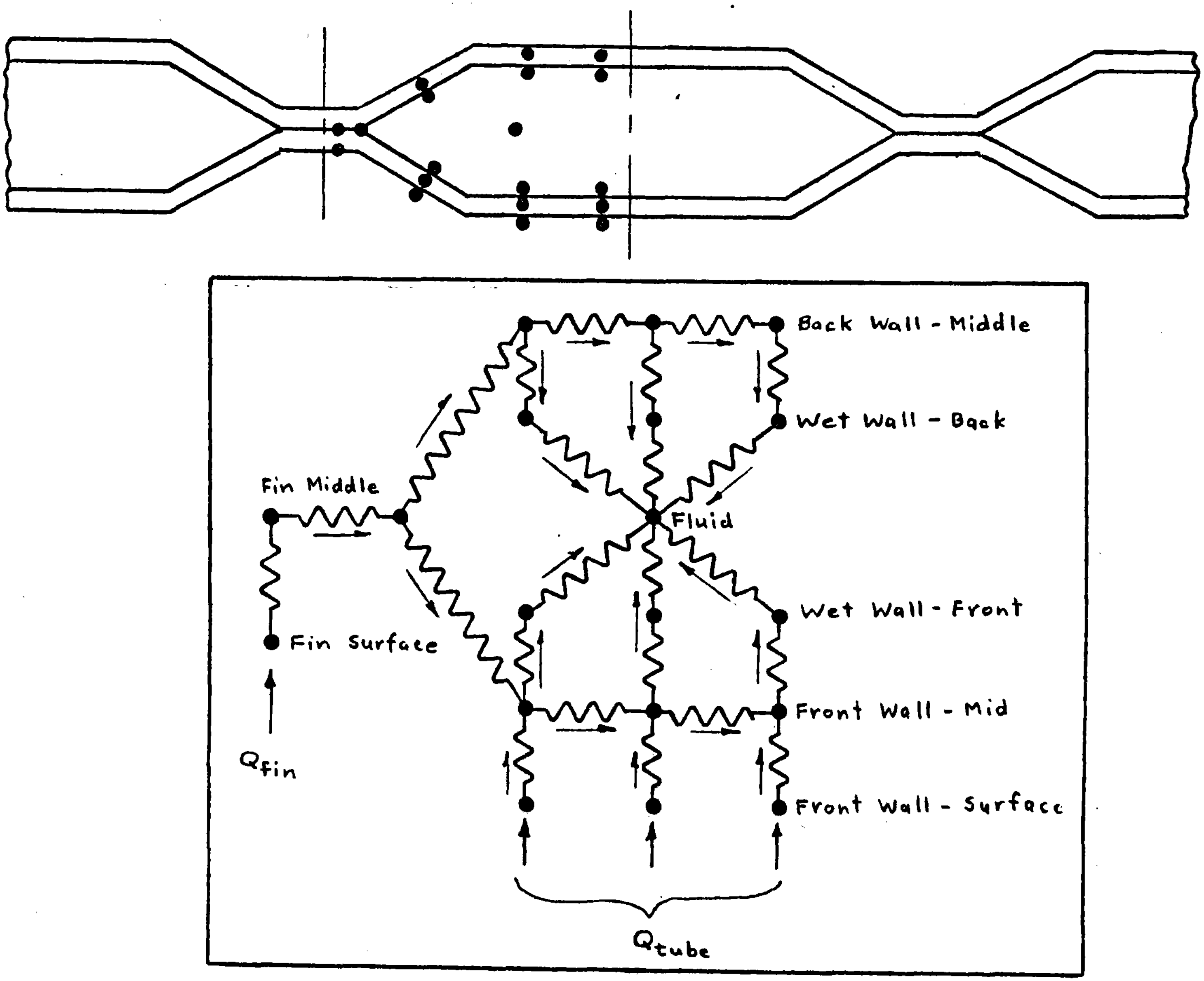



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FIGURE 3.9 SAMPLE COMPUTER PRINT-OUT: "ARCOLES" ANALYZER

```
                              DAY 355 : 12:00 NOON
                              --------------------

NODE # = 67
VIEW FACTOR TO APERTURE= .01519
INCIDENT Q, KW = 207.55
ABSORP.LOSS, KW = 5.98
CONV.LOSS, KW = 2.77
RAD.LOSS, KW = .75
Q INTO FLUID, KW = 198.04
MAXIMUM THERMAL STRESS, PSI= 15534
TEMP OF FIN, DEG-F= 567
TEMP OF FRONT, DEG-F= 497
TEMP OF BACK, DEG-F= 443
TEMP OIL, AVG, DEG-F= 436
TEMP OIL IN, DEG-F= 420
TEMP OIL OUT, DEG-F= 452
AVG OIL DENSITY, LB/CU-FT= 46.011
AVG OIL VISCOSITY, LB/FT-HR= .718
AVG OIL CONDUCTIVITY, BTU/FT-HR-F= .07013
PANEL FLOW RATE, GPM = 95
PANEL FLOW VELOCITY, FT/SEC= 14.68
PASSAGE FILM COEFFICIENT, BTU/SQ-FT-HR-F= 886.83
```

TABLE 3.2 RECEIVER ENERGY, KW, BALANCE & EFFICIENCY

| | Day 355 (Winter Solstice) | | | Day 80 (Equinox) | | | Day 173 (Summer Solstice) | | |
|---|---|---|---|---|---|---|---|---|---|
| PARAMETER | 8:00 | 10:00 | 12:00 | 8:00 | 10:00 | 12:00 | 8:00 | 10:00 | 12:00 |
| Energy Available | 10256 | 12669 | 13021 | 10925 | 12119 | 12512 | 9971 | 11118 | 11509 |
| Energy Losses: | | | | | | | | | |
| 1. Aperture | 416.8 | 305.6 | 239.5 | 593.0 | 415.0 | 327.0 | 733.8 | 579.0 | 495.1 |
| 2. Panel Miss | 88.6 | 143.9 | 164.0 | 70.8 | 124.0 | 146.4 | 39.6 | 91.1 | 113.9 |
| 3. Absorptivity | 277.2 | 343.8 | 353.5 | 294.1 | 327.2 | 338.0 | 265.9 | 297.1 | 307.6 |
| 4. Convection | 385.2 | 408.0 | 411.0 | 390.5 | 401.9 | 405.9 | 381.0 | 391.5 | 395.7 |
| 5. Radiation | 77.9 | 88.2 | 89.7 | 80.5 | 85.4 | 87.2 | 76.0 | 80.6 | 82.1 |
| TOTAL LOSSES | 1246 | 1290 | 1258 | 1429 | 1354 | 1305 | 1496 | 1439 | 1394 |
| ENERGY TO FLUID | 9010 | 11380 | 11763 | 9496 | 10766 | 11208 | 8475 | 9679 | 10115 |
| EFFICIENCY, % | 87.85 | 89.82 | 90.34 | 86.92 | 88.83 | 89.57 | 85.00 | 87.05 | 87.88 |

motor drive electronics, limit switches, and the communications buss to the master control. Each heliostat will receive solar vector cosines, target coordinates and heliostat coordinates. The heliostat coordinates and target coordinates will be down-loaded once per day, the solar vector cosines will be sent periodically.

The processor at each heliostat will recognize mode commands that will cause the heliostat to return to stow positions or to slew to a commanded position. The master control can also interrogate each heliostat as to the status of its limit switches and position registers.

The master control will communicate to the heliostats on a serial data buss with a maximum of 64 heliostats on each buss. The communications will be a duplex data transmission at the rate of approximately 9600 baud.

The output of the master control computer will be buffered so that the data can be transmitted on 6 separate data busses to a maximum of 6x64 heliostats. If redundancy is a requirement, the data will be transmitted on separate lines.

The drive for the stepper motors will consist of solid state power switches in each of the four motor legs ( see figure 3.10). The processor will drive the motor through the step sequence shown in figure 3.11. The motor will be powered down by going into the sleep mode. Sufficient friction in the system will provide the holding torque during the sleep mode.

The microprocessor system is shown in figure 3.12 and consists of a 6504 CPU, 6522 versatile interface adapter, 6532 RAM/timer I-O and 4K ROM chip. The CPU outputs stepper motor commands to the 6532 I-O ports. Eight ports are required to control the two stepper motors. The outputs of the 6532 are buffered and amplified to switch the stepper motor windings.

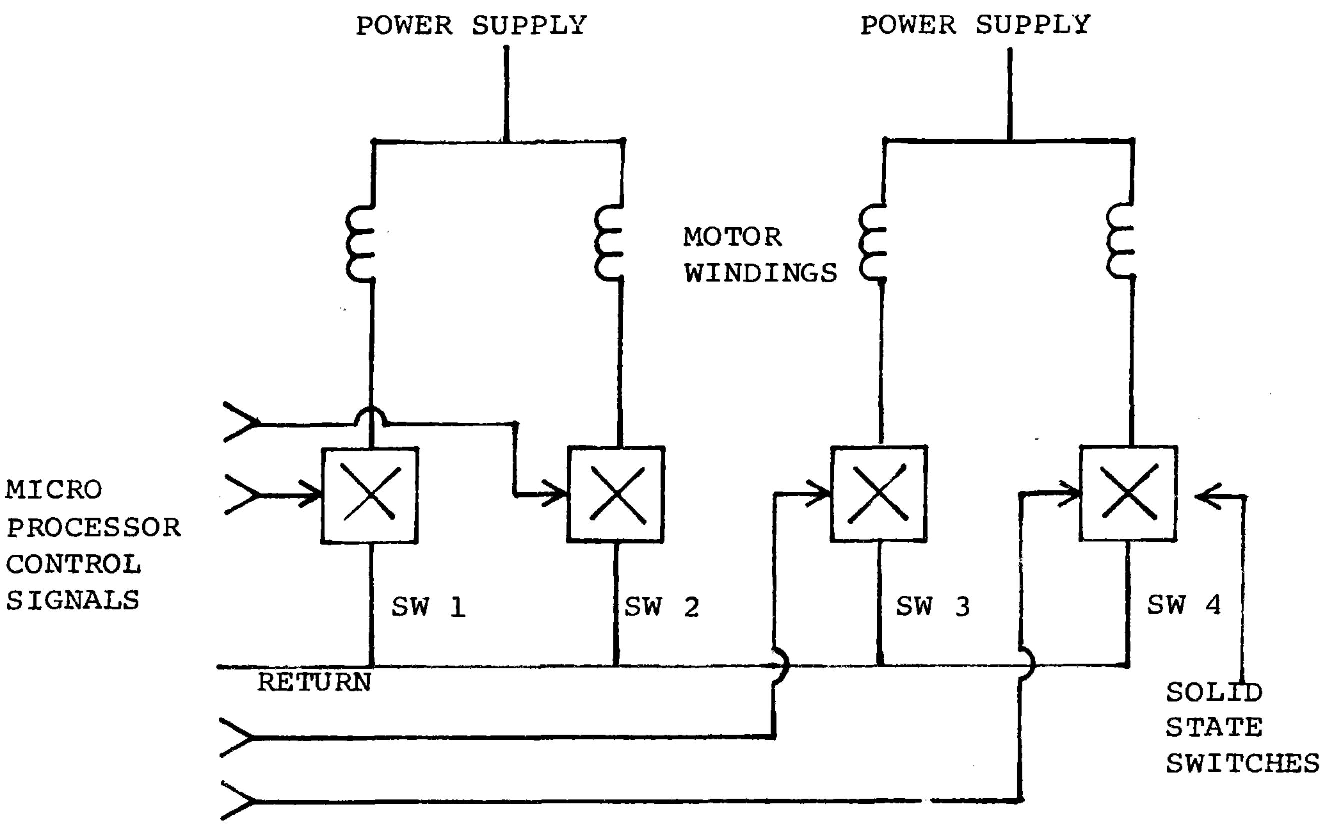



Figure 3.10 Stepper Motor Driver Diagram

| STEP | SW 1 | SW 2 | SW 3 | SW 4 |
|---|---|---|---|---|
| 1 | ON | OFF | ON | OFF |
| 2 | ON | OFF | OFF | ON |
| 3 | OFF | ON | OFF | ON |
| 4 | OFF | ON | ON | OFF |

Figure 3.11 Logic Switching Sequence

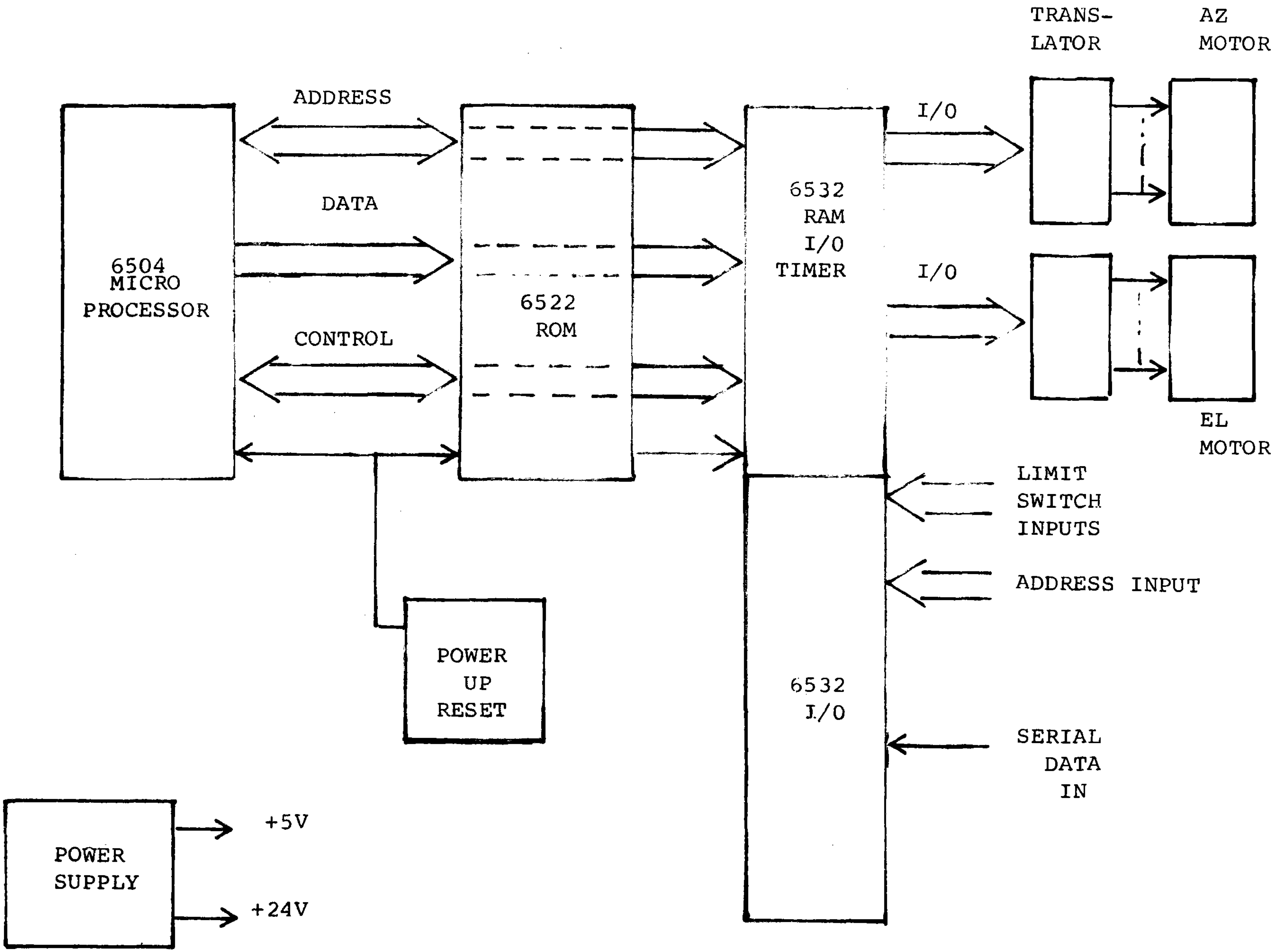



Figure 3.12 Block Diagram — Control Electronics

Limit swiches are read by the 6522 and the data put into the 6532 RAM. Each electronics unit is equipped with dip switches that identify the address of the unit to the master control.

These switch inputs are also read by the 6522. Serial communications is handled by two ports on the 6522 that are used for incomming data. One port is an interrupt input for the 6522 and the other is a data input port. The interrupt port detects the start bit of the data word and the actual data is read from the data port. The outgoing status data comes from another data line of the 6522. The software for the communications is interrupt driven so that calculations can be accomplished while data is being received. Internal timers in the 6522 allow hardware timing during the communications process.

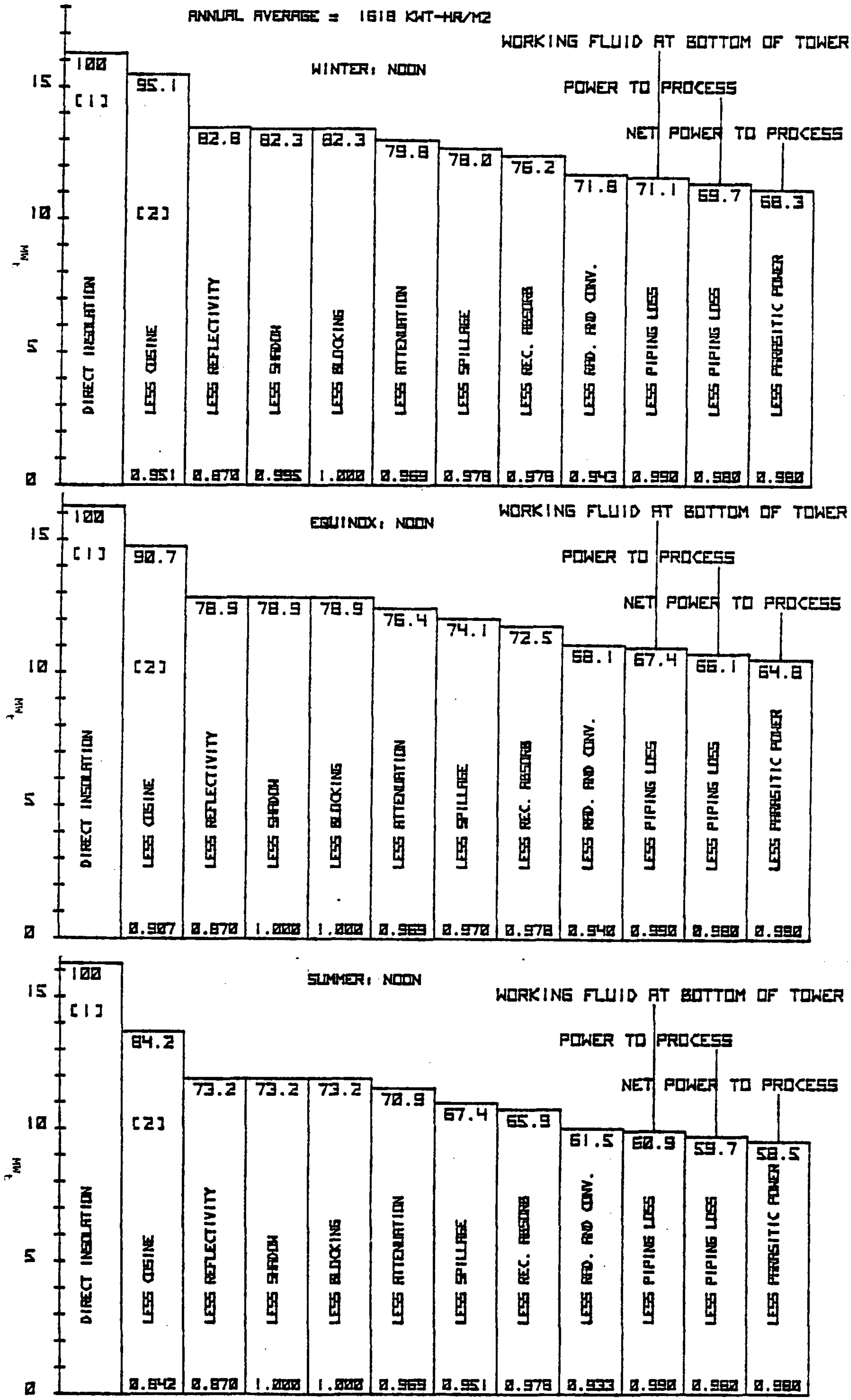
## 4. SYSTEM PERFORMANCE

As discussed in Section 3, the design point was established to be a system that would deliver to the existing system 9,518 $KW_t$ at noon, summer solstice. This effectively supplies all the plant's process heat requirements except the heat, furnished by other sources, that would be wasted if additional heat was supplied by solar. Using this criteria for system rating, the collector field was sized at 320 heliostats.

The stairstep energy accounting technique was used to establish the solar system performance at noon on winter solstice, spring equinox, and summer solstice (design point). These energy stairsteps are presented in Figure 4.1. The average annual energy delivered is $94.56 \times 10^9$ Btu which is approximately 33% of the annual amount ($285 \times 10^9$) furnished by the fired heaters.

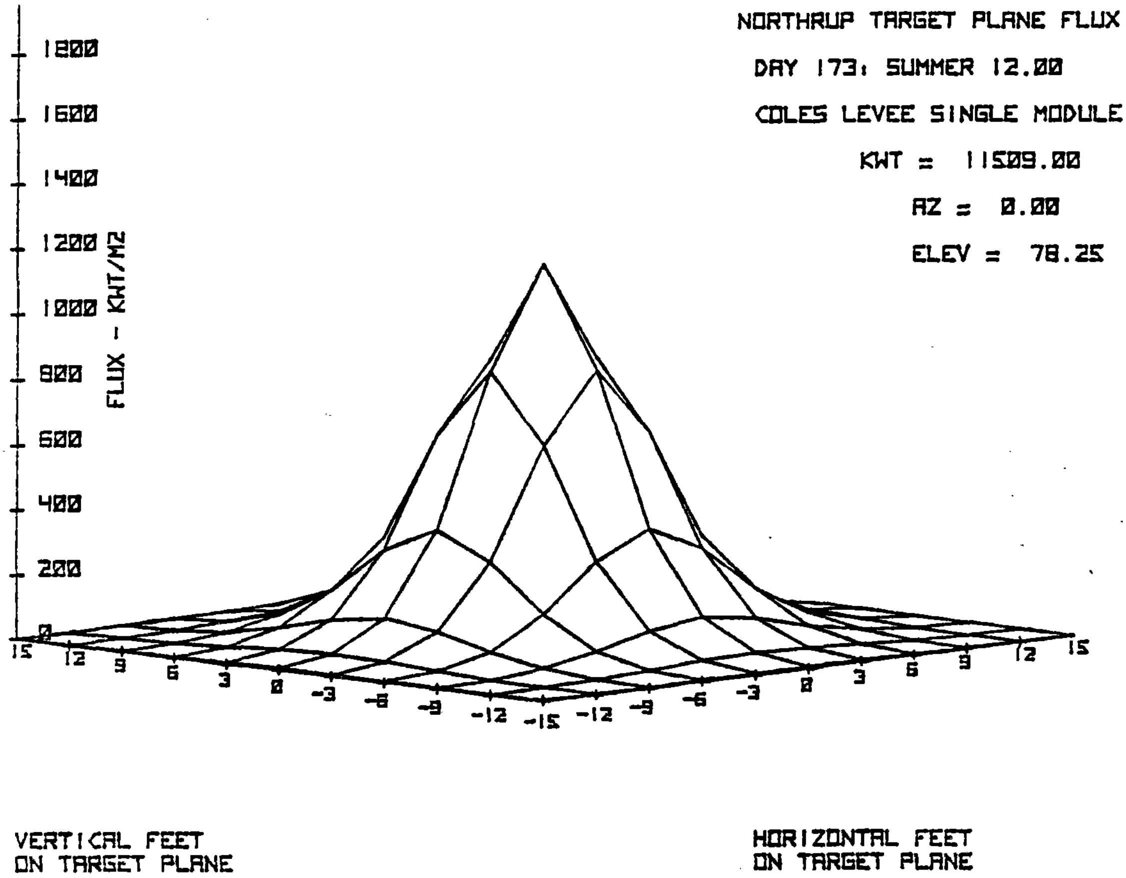
These energy stairsteps are preliminary to the extent that the conceptual design of the receiver and the actual piping layout and sizing has not been completed, hence, the cycle efficiencies for these components are subject to change as the design progresses.

Profiles of the flux incident on the target plane and on the receiver surface (cavity - 24 ft. radius) have been calculated. These profiles were calculated for morning, noon and afternoon times at the summer and winter solstices and the spring equonox. Examples of the flux profiles calculated for noon, summer solstice are presented in graphic form in Figure 4.2. The profiles are being employed in the design and evaluation of the receiver.




[1] - NET CYCLE EFFICIENCY AT EACH POINT [2] - EFFICIENCY OF EACH CONVERSION STEP

Figure 4.1 PROCESS HEAT STAIRSTEPS FOR NOON ON WINTER, EQUINOX AND SUMMER SOLSTICES



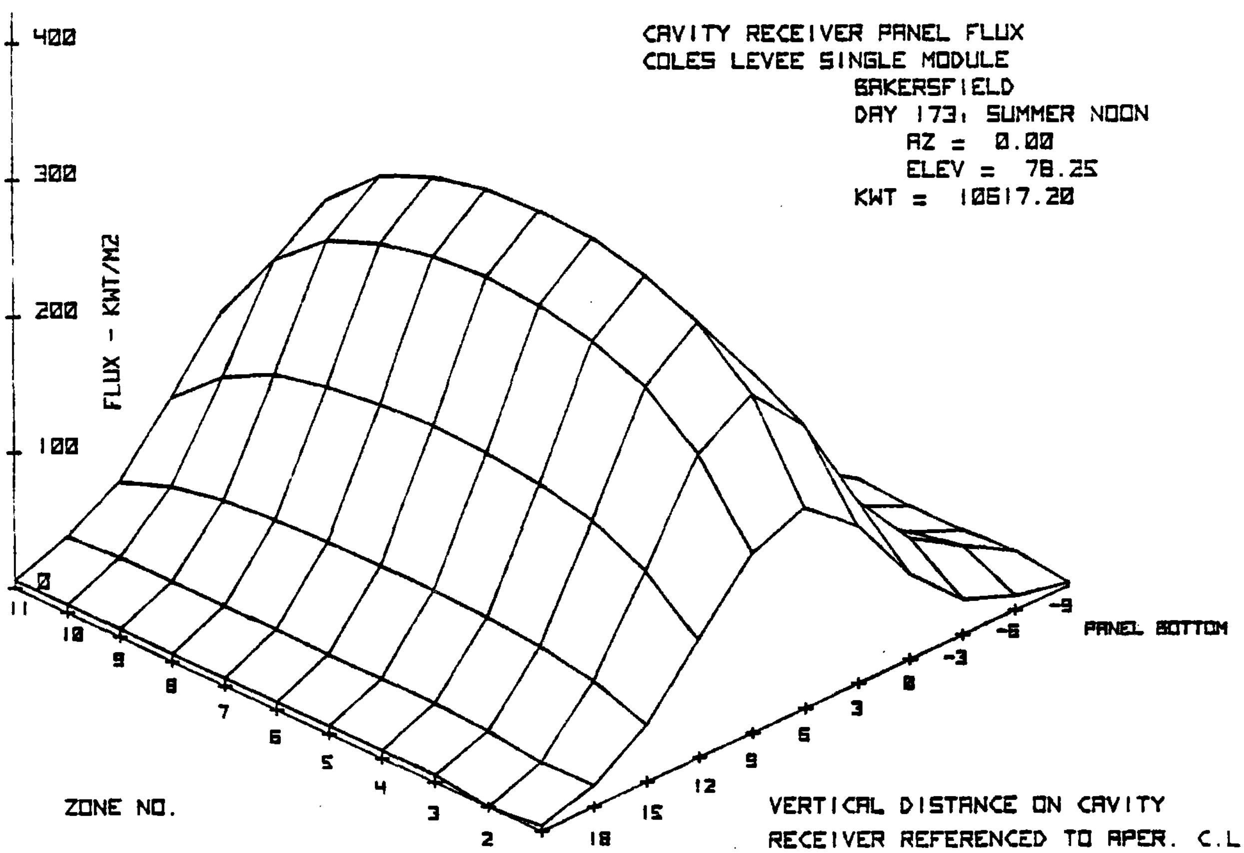






Figure 4.2 ENERGY FLUX PROFILES INCIDENT ON THE TARGET PLANE AND RECEIVER AT THE NOON, SUMMER SOLSTICE DESIGN POINT