PN-AAW-663
ISN 4[illegible]
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SOLAR HOT WATER SYSTEM

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Training on alternative energy technology (TAET)
Session II
September - December 1980
University of Florida
(Trace Center)
Gainesville, Florida

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A Introduction

Industrial processes consume much energy. Most of these processes require energy as heat at temperatures below 150°F.

Primary energy sources at present are oil, natural gas and coal, which feed hot water boilers, which supply heat to various processes. These sources of energy are rapidly depleting. Their prices are increasing continuously. It has now become necessary to look for alternative energy sources.

Solar energy, Nuclear energy, wind energy Geothermal energy, ocean thermal energy, energy from biomass etc are various alternative energy sources. Each of these sources has its advantages and disadvantages.

Solar energy is free and inexhaustible. Use of Solar energy poses no environmental hazard. However solar energy is diffused and requires large area for collection and utilisation. Hence the initial investment on solar installations is very high.

This project deals with the design of a solar water heating system using flat plate collectors and the economics of using such systems for industrial process heat applications.

B. Objective

The objective of this report is to present a simple procedure for designing a solar hot water system and for determining the economics of this system.

C. Design Calculations

1. Data

Fuel used in the existing boiler	oil (bunker)
Heating value of fuel oil	6.3×10^6 BTU/bbl
Cost of fuel oil	\$ 36.71 / bbl
Efficiency of boiler system, η_b	65 %
Average tap water temperature, T_i	75° F
Monthly average daily insolation on horizontal surface[1]	2305 BTU/ft^2
Roof area available for flat plate collectors installation	35,640 ft^2
Latitude of Gainesville	29° 39'
Winter declination of sun	23° 27' S
Volume of water to be heated	25,000 gals/day
Temperature of hot water, T_f	140° F
Efficiency of collectors, η_c	40 %
Collector orientation	South facing
Collectors tilt to horizontal	40°
Heat loss factors for storage and piping (assumed)	0.10
Efficiency of pump, η_p	50 %

2. Daily heat requirement

$$Q_W = \dot{m} \times C_p \times (T_f - T_i)$$
$$= 25{,}000 \text{ gal} \times 8.3 \text{ lbs/gal} \times 1 \text{ BTU/lb/}^\circ F \times (140-75)^\circ F$$
$$= 13{,}437{,}500 \text{ BTU/day}$$

3. Monthly average daily insolation on inclined surface

$$\overline{H_T} = \overline{R} \times \overline{H}$$
$$\overline{R} = (1 - \overline{H_d}/\overline{H})\,\overline{R_b} + \overline{H_d}/\overline{H}\,(1+\cos\theta)/2 + r\,(1-\cos\theta)/2$$

$\overline{H_d}/\overline{H}$ is obtained from a graph $\overline{H_d}/\overline{H}$ v/s K_T given in reference 2 $\overline{H_d}/\overline{H}$ for gainesville $= 0.26$

r, ground reflectance $= 0.2$ (assumed)

$\overline{R_b}$, the ratio of direct radiation on inclined surface to direct radiation on horizontal surface is also obtained from a graph $\overline{R_b}$ v/s collector tilt given in reference 2.

$(1+\cos\theta)/2 = 0.893$, $(1-\cos\theta)/2 = 0.117$

$$\overline{R} = 0.91 \times 0.74 + 0.26 \times 0.893 + 0.2 \times 0.117$$
$$= 0.95$$
$$\overline{H_T} = 0.95 \times 2805 \text{ BTU/ft}^2\text{/day} = 2334.3 \text{ BTU/ft}^2\text{/day}$$

4. Area of collectors.

$$A_c = \frac{Q_W}{\overline{H_T} \times \eta_c \times \eta_{eff}}$$
$$= \frac{13{,}437{,}500 \text{ BTU/day}}{2334.3 \times 0.4 \times 0.9 \text{ BTU/ft}^2\text{/day}}$$
$$= 15714 \text{ ft}^2$$

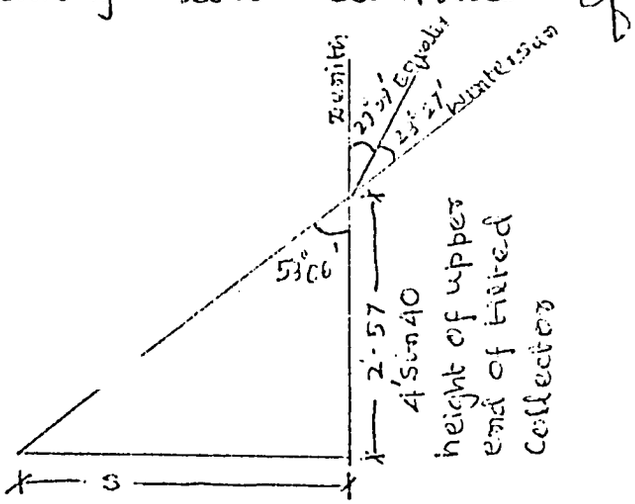
5. Collector layout

No: of (8'x4') collectors required $= \dfrac{15714 \text{ ft}^2}{32 \text{ ft}^2 \text{ per piece}}$

$= 492$ pieces

Nine rows of collectors with 56 collectors in each of the first eight rows and the rest 44 collectors in the final row.

Distance between collector rows is calculated to avoid shadow of one row of collector falling on the next during low altitude of the sun



$$S = 2'\cdot57 \times \tan 53^\circ 06' \simeq 3'\cdot5$$

Distance between two collector rows 3'-6"

Length of the building 540'
Width of the building 66'

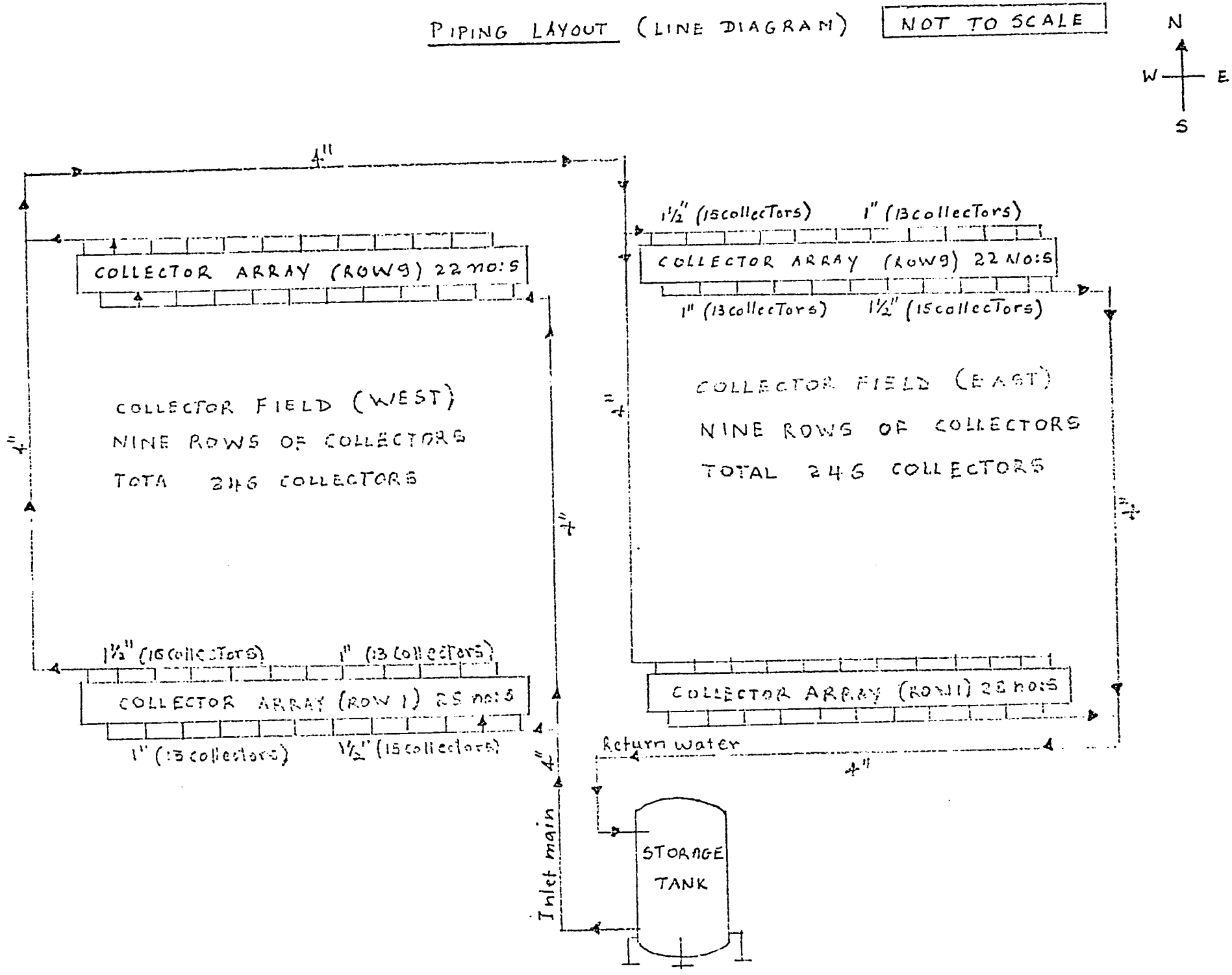
Along the length :-

$$\Big[\underset{\text{(end clearance)}}{35'-6''} + \underset{\text{(collector length + gap)}}{8' + 3''} \times \underset{\text{no. of collectors}}{27} + \underset{\text{collector length}}{8'} + \underset{\text{Half central gap}}{3'-9''}\Big] \times \underset{\text{two groups}}{2} = 540$$

along the width :-

$$\underset{\text{(end clearance)}}{5'-6''} + (\underset{\text{(collector + gap)}}{3' + 3'-6''}) \times \underset{\text{(rows)}}{8} + \underset{(9^{th}\text{ row})}{3'} + \underset{\text{(end clearance)}}{5'-6''} = 66'$$

PIPING LAYOUT (LINE DIAGRAM) NOT TO SCALE



6. Storage tank Sizing:

Three major factors determine the optimum capacity of storage system. They are

a. The cost of the storage unit, which includes the cost of containers, cost of storage medium, cost of space in which the container is located, etc.

b. The effect of storage capacity on the operation of the rest of the system, particularly collectors.

c. Thermal losses from the storage unit.

Based on the many simulation studies done to assess the effect of storage capacity on long term system performance Klein, and et all suggest 7.5 liters of stored water per square foot of collector. This value is used in sizing the storage tank used for the present system.

$$\text{Storage capacity} = 7.5\ \ell/ft^2 \times \frac{1}{3.79\ \ell/gal} \times 15714\ ft^2$$

$$\simeq 31097 \text{ gallons}$$

$$\simeq 4146 \text{ or } ft^3$$

$$\text{Height reqd for a } 12' \text{ dia storage tank} = \frac{4146\ ft^3}{\pi \times 12^2/4\ ft^2}$$

$$= 36.7\ ft$$

Add 8' for top and bottom clearance

Total Height of the storage tank = 45 ft

7. Pipe Sizing

For medium temperature collectors such as the ones in the present system, a flow of 0.03 gallon per minute for each square feet of collector is found to be adequate. (Refer pipe layout drawing) There are two fields of collectors in series.

Hence total flow required $= 0.03 \frac{gal/m}{ft^2} \times \frac{15714}{2} ft^2$

$= 235.71$ gpm or $31.5 ft^3/min$

$0.52 ft^3/sec$

Diameter of the pipe at various sections are determined by limiting the velocity in the pipes to about 5-8 ft/sec and using the relationship

$$q = v \times \frac{\pi d^2}{4}$$

For example: $q = 0.52 ft^3/sec$ $v = 5 ft/sec$

$$\therefore d = \sqrt{\frac{0.52 \times 4}{5 \times \pi}} = 0.37' \text{ or } 4.4''$$

If 4" diameter pipe is used velocity in the pipe $V = \frac{0.52 \times 4}{\pi \times (0.333)^2} = 5.95$ ft/sec O.K.

8. Pressure drop calculation

Design of pipe layout is such that the pressure drop through each path of flow in the field is the same. (Refer Fig. 1)

Pressure drop across a collector is 0.6' as given in the USSC design manual. (U.S. Solar corporation)
Pressure drop in the connecting pipes can be calculated using the formula $h_f = f \frac{l}{d} \times \frac{V^2}{2g}$

friction factor, f, can be obtained from the Moody's chart knowing the Reynold's number (Re) for the flow and the relative roughness of the pipe.
For example:

Re for the flow in the inlet main $= \frac{\rho V d}{\mu}$

ρ density of water, depends on temperature & pressure

$$\rho_{75°F, atm} = 62.32 \text{ lb/ft}^3$$

$$V_{inlet\ main} = 5.95 \text{ ft/sec}$$
$$d = 0.333 \text{ ft}$$

μ, the dynamic viscosity also depends on temperature and pressure

$$\mu_{75°F, atmpr} = 19.5 \times 10^{-6} \text{ lbf sec/ft}^2$$

$$\therefore Re = \frac{62.32 \text{ lb/ft}^3 \times 5.95 \text{ ft/sec} \times 0.333 \text{ ft}}{19.5 \times 10^{-6} \text{ lbf sec/ft}^2}$$

$$= 6.33 \times 10^6$$

For a smooth pipe this corresponds to a friction factor of "0.0085".
At higher temperature the dynamic viscosity reduces considerably.
For our head loss calculations, we adopt $f = 0.0085$

consider a path wherein the friction head would be representative of the friction head in all the paths.

Total length of 4" pipe ≃ 800 ft
Total length of 1½" pipe ≃ 500 ft
Pressure drop across collector = 0.6 ft

$$\therefore \quad h_f = 0.0085 \times \frac{800}{0.333} \times \frac{(5.95)^2}{2 \times 32.2} + 0.0085 \times \frac{500}{0.125} \times \frac{5.95^2}{2 \times 32.2} + 0.6 + 0.6$$

$$= 11.23 + 18.69 + 0.6 + 0.6$$

$$= 31.12 \text{ ft}$$

Add ≃ 30% to account for losses in the bends, fittings etc

∴ total friction head loss ≃ 40 ft

This does not include the static head, the head equivalent to the height of the building. This system will be designed to have two pumps. One reciprocating pump which will overcome static head and another Booster pump to keep the water in circulation.

9 Pump Sizing

Booster pump $\quad p = \frac{\gamma \cdot w h_f}{\eta_p}$

$$p \text{ in ft lb/min} = \frac{31.5\ ft^3/min \times 62.4\ lbs/ft^3 \times 40\ ft}{0.5}$$

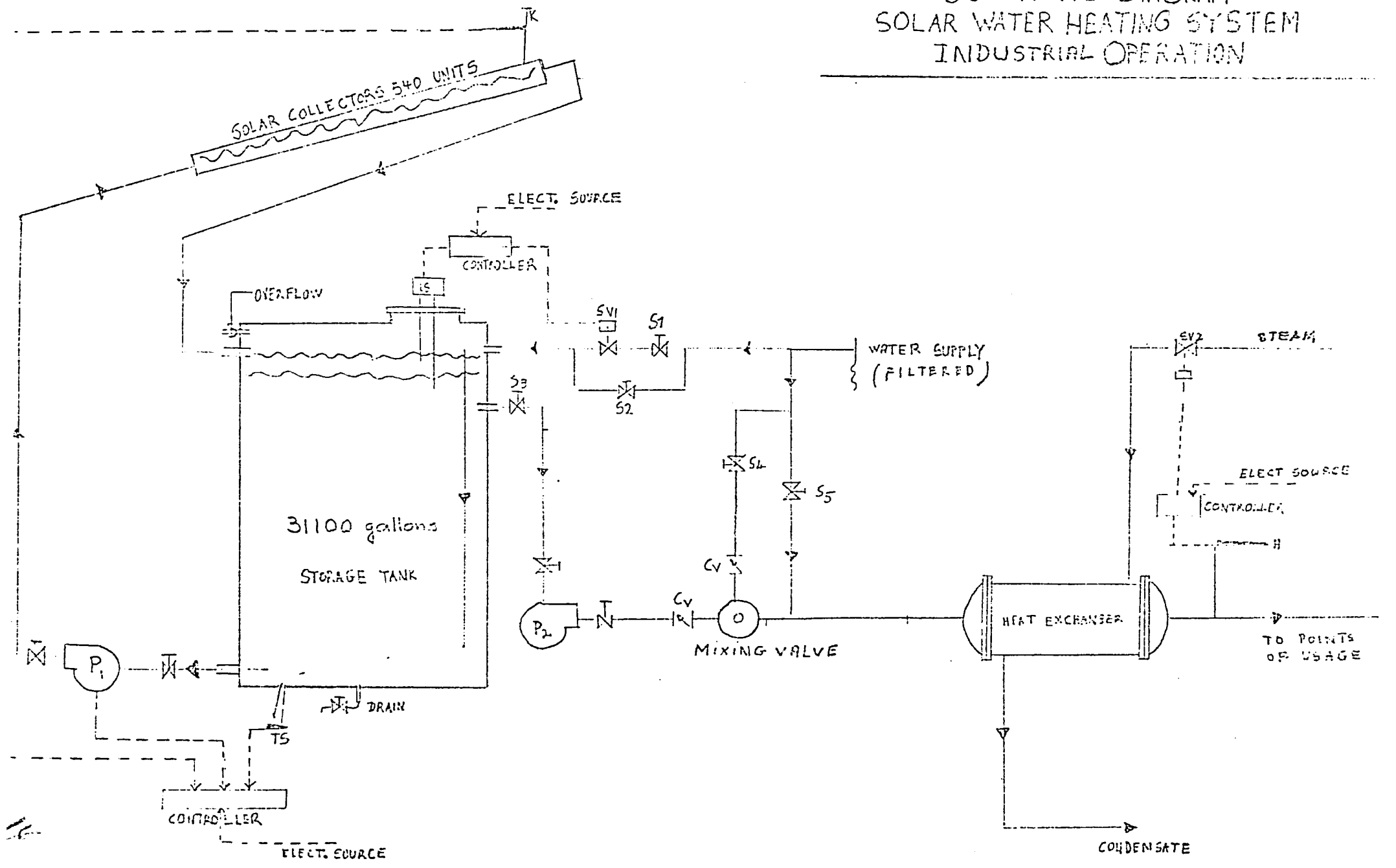
$$= 157248 \text{ ft lb/min}$$

$$33000 \text{ ft lb/min} = 1 \text{ hp}$$

$$p = \frac{157248}{33000} = 4.72 \text{ hp}$$

Provide the nearest available 5 hp pump as the booster pump.

SCHEMATIC DIAGRAM
SOLAR WATER HEATING SYSTEM
INDUSTRIAL OPERATION



D - Economic analysis

1- Data

Heating Value of fuel oil, H.V	6.3×10^6 Btus/bbl
Cost of fuel oil as on date (Dec 1980)	\$ 36.71 /bbl
Efficiency of boiler system, η_b	65%
Total cost of Solar System installed	\$45/ft^2
Fuel cost ~~inflation~~ annual rate of increase	12% per year
Maintenance cost per year	1% of Total cost
General inflation rate	8%
Interest on investment	16%
Life of Solar System	20 years.

2. Number of working days in a year

$= 365 - 52 - 10 - 10$
(Sundays) (Public holidays) (Maintenance)

$= 293$ days

3. cost of fuel oil used to heat water using existing boiler system 'C'

$$C = \frac{\dot{m} \times C_p \times (T_f - T_i)}{\eta_h \times H.V} \times \text{cost of oil per bbl}$$

$$= \frac{25{,}000 \text{ gal/day} \times 3.34 \text{ lbs/gal} \times 1 \text{ Btu/lbf°F} \times (140-75)°F}{0.65 \times 6.3 \times 10^6 \text{ Btus/bbl}} \times \$36$$

$\simeq \$ 121.47$ per day

Cost of fuel oil per year (1981) $= 293 \times \$121.47$
$= \$35,590.71$

4. Auxiliary heating required for solar system.

The solar system is designed for maximum insolation in a year. This occurs during the month of May. Rest of the year, when insolation is less, auxiliary heating will be used. ~~to supply~~

Average of difference in monthly average daily insolation over the year is calculated. About 10% of yearly heating load is calculated to be met by auxiliary heating.

Existing boiler will be used for auxiliary heating.

Cost of oil required for auxiliary heating $= 0.10 \times \$35,590.71 = \$3,559.07$ $\$355.91$

5 calculation of solar savings

Solar Savings = Fuel Savings + Tax Savings − Maintenance cost − auxiliary heating cost

Table 1 lists the solar savings for each year from 1991 to 2000

6. cost of solar system

Total cost of solar system was assumed to be \$ 45 times the area of collectors installed

$$C_{ss} = 45 \ \$/ft^2 \times 15714 \ ft^2$$

$$= \$ \ 707,130.$$

7. Based on Federal laws (1950) the capital investment for industrial use are deductible from the income tax payment.

15% of cost of any new equipment
+ 10% of cost of new equipment for solar energy utilisation

Therefore at the end of the first year, there will be a savings of 25% of \$ 707,130 or \$ 176,783

Table 1. Solar Savings. (in $s)

	Savings	Cost of auxiliary heating	Cost of Maintenance	Net Savings
1	35,591 + 176,753	35,59	7,071	201,744
2	39,862	3,986	7,637	28,239
3	44,645	4,465	8,248	31,933
4	50,003	5,000	8,907	36,096
5	56,003	5,600	9,620	40,783
6	62,724	6,272	10,390	46,061
7	70,250	7,025	11,220	52,005
8	78,680	7,868	12,118	58,695
9	88,122	8,812	13,088	66,222
10	98,697	9,870	14,135	74,692
11	110,540	11,054	15,266	84,221
12	123,805	12,381	16,487	94,938
13	138,662	13,866	17,806	106,990
14	155,301	15,530	19,230	120,541
15	177,937	17,794	20,769	135,775
16	194,809	19,481	22,430	152,898
17	218,187	21,819	24,225	172,143
18	244,369	24,437	26,163	193,769
19	274,693	27,469	28,256	218,068
20	306,536	30,654	30,516	245,367

6. Calculation of Return on investment.

Discount rate that will give a zero life cycle savings for solar systems is called the return on investment in solar systems.

Finding the return on investment is a trial and error process. Life cycle savings is obtained by discounting each annual savings to its present value and finding the sum of these discounted savings.

Table 2 lists the discounted savings for each year from 1981 to 2000.

Table 2 Discounted cash flow

YEAR	Cash Flow Out	Cash Flow Net in	P.V. Factor @ 10.7%	Present Value	
0	707,130		1		
1		201,744	0.9033	182,235	
2		23,239	0.8160	23,043	
3		31,933	0.7372	23,541	
4		36,096	0.6654	24,046	
5		40,783	0.6015	24,531	
6		46,061	0.5434	25,030	
7		52,005	0.4907	25,529	
8		58,695	0.4434	26,025	
9		66,222	0.4006	26,529	
10		74,692	0.3618	27,024	
11		84,221	0.3269	27,532	
12		94,938	0.2953	28,035	
13		106,970	0.2667	28,534	
14		120,541	0.2410	29,050	
15		135,775	0.2177	29,558	
16		152,895	0.1966	30,060	
17		172,143	0.1776	30,573	
18		193,769	0.1605	31,100	
19		218,068	0.1449	31,598	
20		245,367	0.1309	32,119	Difference
				705,682	1,448

E - Conclusions

The authors recommend that the procedure given in this report be adopted as a guide to the design and economic analysis of Solar water heating systems

The authors further recommend that the succeeding participants of the Training in Alternative Energy Technologies programme continuously improve the procedure and update the figures used in the calculations

F. Appendices

31. Specifications

1 Flat plate collectors.

Flat plate collectors shall have an assembly of absorber plates with copper tubes, half inch internal diameter compressed into aluminium fin and brazed to manifolds three fourth inch internal diameter. The absorber plates shall be coated with maximum heat absorption paints with absorptivity 0.98 and emissivity - 0.89. Absorber plates shall be enclosed in rigid anodized aluminium frame (4' x 8' having sufficient strength to withstand a pressure of 84 psf during high winds, when installed in the field. closed cell insulation of atleast 1¼" thickness with aluminium foil sidings shall be used to insulate the absorber plates at the back and the sides. The Glass cover shall be water white tempered glass with transmittance 0.92 The collectors shall have a time constant of 2 minutes. The collectors shall conform to Florida Solar Energy center Test methods and minimum standards for solar collectors, FSEC 1977. The Efficiency curve of the collectors shall be such that at the operating temperatures (75-140°F) collectors efficiency shall be atleast 40 percent.

Design life of the collectors shall be minimum thirty years and shall carry a warranty for any defects in materials or workmanship for atleast five years.

2. Storage tank.

A cylindrical storage tank made of half inch thick M.S plates shall be used for the system. It shall be 12 feet in internal diameter and 45 feet in height. It shall be internally lined to prevent rust, scale and galvanic corrosion. It shall be insulated with six inch thick urethane foam. This insulation shall be protected from rain with aluminium foils strapped to the outside. It shall be stratified. The inlet header and the outlet shall be so designed as to not to disturb the stratification in the storage tank. It shall have air vents, drain holes and cathodic protection rods.

3. Pipes.

The connecting pipes shall be four inch Galvanised ~~copper~~ flow pipes. They shall be covered with 3" thick urethane foam insulation on the outside. This insulation shall be protected from rain by aluminum foil covers strapped to the outside.

4. Pumps

A 5 hp centrifugal pump capable of delivering 236 gpm shall be used in the system for circulating water.

A reciprocating pump shall be used to fill up the collectors at the time of starting the system.

5 Differential Temperature controller.

5 Differential temperature controller consisting of a durable solid state unit enclosed in steel box and two precision matched heat sensors shall be used to activate the circulation pump when the temperature of the collector plate is 10°F above the temperature of water inlet and stop the circulation pump when the collector plate temperature is 5°F below the inlet water temperature.

6. Automatic air vents

Automatic air vents shall be provided to prevent airlock in the system.

7. Freeze protection

Two frost sensors shall be used to protect the collectors and exposed pipes from freezing. These sensors shall activate the circulation pump during freezing temperatures, circulating water. When the collectors and pipes are warm enough the pump will be switched off automatically.

2. NOMENCLATURE

Q_w	Water heating load in BTUs
$\dot{m}$	weight of water to be heated per day in lb
C_p	Specific Heat of water in BTU/lb/°F
T_i	inlet water temperature
T_f	outlet water temperature
$\overline{H_T}$	Monthly average daily radiation on a tilted surface
$\overline{H}$	Monthly average daily radiation on a horizontal surface.
$\overline{R}$	Ratio of the monthly average daily radiation on a tilted surface to that on a horizontal surface
$\overline{H_d}$	Monthly average diffused radiation
$\overline{R_b}$	Ratio of monthly average daily direct radiation on the tilted surface to that on a horizontal surface.
θ	Tilt of the collector surface from Hzl.
ρ	ground reflectance
$\overline{K_T}$	Ratio of monthly average daily total radiation to Extraterrestrial daily insolation
η	efficiency of collector
η_{p+s}	Efficiency of piping and storage
A_c	area of collector in ft^2
q	flow rate in ft^3/sec
v	Velocity of water in pipes ft/sec
d	diameter of pipe
h_f	pressure drop in ft.
f	friction factor
l	length of pipes
P	Power required for the pump.

5 REFERENCES

1. Solar insolation on a horizontal surface in Gainesville compiled by "Dr. E. A. Farber"
2 Solar heating design by the 'f'-chart method William. A. Beckman, Sanford. A. Klein, John A. Duffie.
3. Mark's standard Handbook for Mechanical Engineers
4. U.S. solar corporations design manual. 1979.