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### **Author**

Dayan, J.

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# Lawrence Berkeley Laboratory

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## ENERGY & ENVIRONMENT DIVISION

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FOR A STEAM SOLAR ELECTRIC PLANT

Joshua Dayan, Scott Lynn and Alan Foss

July 1979

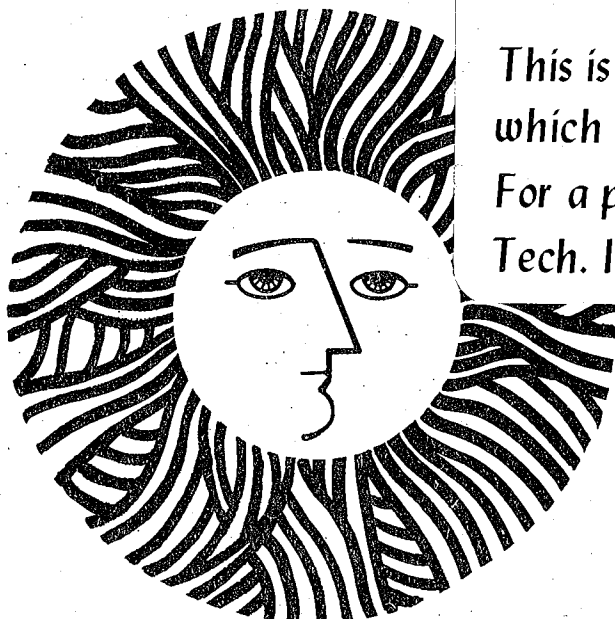
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EVALUATION OF A SULFUR OXIDE CHEMICAL HEAT STORAGE PROCESS  
FOR A STEAM SOLAR ELECTRIC PLANT<sup>\*</sup>

Joshua Dayan, Scott Lynn, and Alan Foss

This report is a revision and condensation of the Master of Science Thesis of Steven A. Hill, Department of Chemical Engineering, University of California, Berkeley, June 1978.

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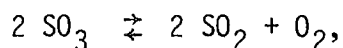
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## SUMMARY

Economical energy storage is essential if solar power plants are ever to supply a significant fraction of the needs of a power grid. The purpose of this study was to develop and evaluate technically feasible process configurations for the use of the sulfur oxide system,



in energy storage. The forward reaction for this system is endothermic and can be used to absorb energy. The reverse reaction is exothermic and releases the energy that has been stored. In this study the storage system is coupled with a conventional steam-cycle power plant. Heat for both the power plant and the storage system is supplied during sunlit hours by a field of heliostats focussed on a central solar receiver. When sunlight is not available, the storage system supplies the heat to operate the power plant.

In this report a technically feasible, relatively efficient configuration is proposed for incorporating this type of energy storage system into a solar power plant. Complete material and energy balances are presented for a base case that represents a middle range of expected operating conditions. Equipment sizes and costs were estimated for the base case to obtain an approximate value for the cost of the electricity that would be produced from such an installation. In addition, the sensitivity of the efficiency of the system to variations in design and operating conditions was determined for the most important parameters and design details.

In the base case the solar tower receives heat at a net rate of  $230 \text{ MW}_t$  for a period of eight hours. Daytime electricity is about  $30 \text{ MW}_e$ . Nighttime generation is at a rate of about  $15 \text{ MW}_e$  for a period of sixteen hours. The overall efficiency of converting heat into electricity is about 26%. A similar steam-cycle power plant without a storage system would operate at an efficiency of about 40%, but would have no nighttime capability. The total capital cost for the base case is estimated at about \$68 million, of which about 67% is for the tower and heliostats, 11% is for the daytime power plant, and 22% is for the storage system. If the base case is compared to a daytime-only steam-cycle solar power plant, then about two-thirds of the cost of the heliostats and receiver must also be ascribed to the storage feature. The average cost of the electricity produced for the base case is estimated to be about  $11\text{¢}/\text{kW}_e\text{-hr}$ .



## I. INTRODUCTION

Some means of high-temperature heat storage for solar power plants is needed as a buffer against short-term interruption of insolation and as a heat source for operation after sundown. Reported here is the development and evaluation of a chemical process, integrated with the central receiver of a solar plant, that absorbs heat during the day by an endothermic chemical reaction, stores the heat as the internal energy of stable chemical compounds at ambient temperature, and releases heat when needed by reversal of the chemical reaction. The chemical reaction employed is the reversible, catalyzed reaction  $\text{SO}_3 \rightleftharpoons \text{SO}_2 + 1/2\text{O}_2$ .

The general idea of the storage process is that the sulfur-oxygen compounds are used as thermodynamic substances in a cyclic process. During the day,  $\text{SO}_3$  is dissociated, absorbing heat, into  $\text{SO}_2$  and  $\text{O}_2$ ; during the night, the  $\text{SO}_2$  and  $\text{O}_2$  are recombined, releasing heat, to form  $\text{SO}_3$ , completing the cycle. One of the favorable characteristics of this chemical system is that  $\text{SO}_2$  and  $\text{SO}_3$  are storable as liquids at ambient temperature; oxygen, however, must be stored as a gas.

It is required by thermodynamics that heat be absorbed at a higher temperature than it is released in a system of this type. Two of the attributes of the sulfur oxide system are that the required heat-absorption temperature is technically attainable in current central receiver designs and that the heat-release temperature is suitable for the generation of power-plant quality steam. The storage system is therefore operated in parallel with a solar-heated steam power plant during daylight hours and supplies the heat for the power plant at night.

The objective of this work is the synthesis and evaluation of such a chemical storage system, integrated effectively with the central receiver and steam turbine portions of the plant. This involves the development of designs for the high- and low-temperature chemical reactors, heat recovery trains, and heat integration; evaluation of energy efficiency; and estimation of equipment size and costs. Attention is confined to storage-related portions of the plant; heliostat and central receiver designs, for example, are not a part of this work.

The process reported here has been developed for a single set of specifications and design parameters and may therefore be considered a "base-case" design. In addition, the sensitivity of the system performance to changes in the specifications and design parameters has been investigated and is treated in Chapter VII of this report. Two important specifications were set for the base case to fix its size and ability to function. The first is that the total thermal input to the central solar receiver was fixed at 230 MW<sub>t</sub>, in accordance with the design by Boeing [5]. Second, the ratio of thermal inputs in the receiver for the daytime power plant and the storage system was set at 1.05, for reasons that are discussed in Chapter VIII. The temperature at which heat is dissipated to the environment is taken to be 60°C to reflect conditions met in a desert environment. In the base case, the storage system is charged during 8 hours of daylight and discharged during 16 hours of nighttime operation. The operations are assumed to be under constant insolation or load. The power output during daytime operation is about 31 MW<sub>e</sub>. At night it would be about half that value for a constant rate of discharge. For the case where a larger power

plant is desired the choice will have to be made between scaling up the Boeing receiver and installing multiples of the present design.



## II. DAYTIME OPERATION: The Charging System

### A. General Description of the Process

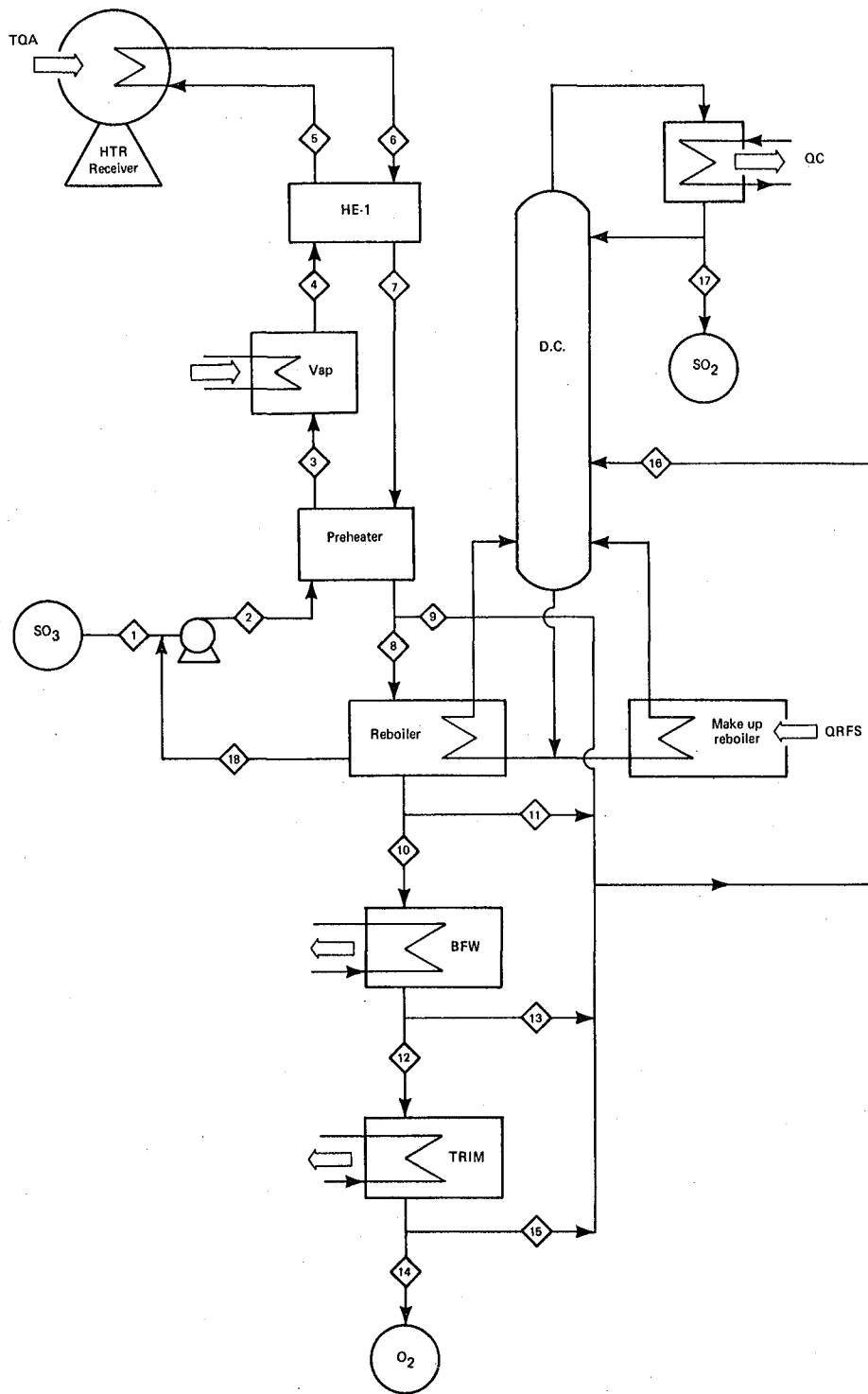
A detailed flow sheet for the high-temperature side, or charging side, of the process is shown in Figure 2.1. Properties and flow rates of each of the numbered streams are given for the base case in Table 2.1. To fully fix the conditions of all streams, the following set of five parameters must be specified; the values given here are for the base case:

Minimum discharge temp., $T_{\min}$ :	60°C
Maximum reactor wall temp., $T_{\max}$ :	880°C
Reactor feed-effluent $\Delta T$ , ( $T_6 - T_5$ ):	140°C
Reactor pressure:	40 atm
Distillation column pressure:	11 atm

The major components of the process are:

1) The receiver/high-temperature reactor (Figure 2.2): Sunlight reflected from the mirror field enters the aperture at the bottom of the receiver and is eventually absorbed by the process gas flowing through the receiver tubes. These tubes are coated internally with  $\text{Fe}_2\text{O}_3$ , which catalyzes  $\text{SO}_3$  dissociation at high temperature. The process gas, at 40 atmospheres, absorbs the incoming heat mostly by reacting but also by rising in temperature.

2) Heat Exchanger 1: This heat exchanger transfers excess heat from the reactor exit gas to the incoming reactants. Thus, the sensible-heat rise experienced by the reaction gas in the reactor is used to preheat the reactor fuel to a temperature at which the catalyzed dissociation of  $\text{SO}_3$  occurs quite rapidly.



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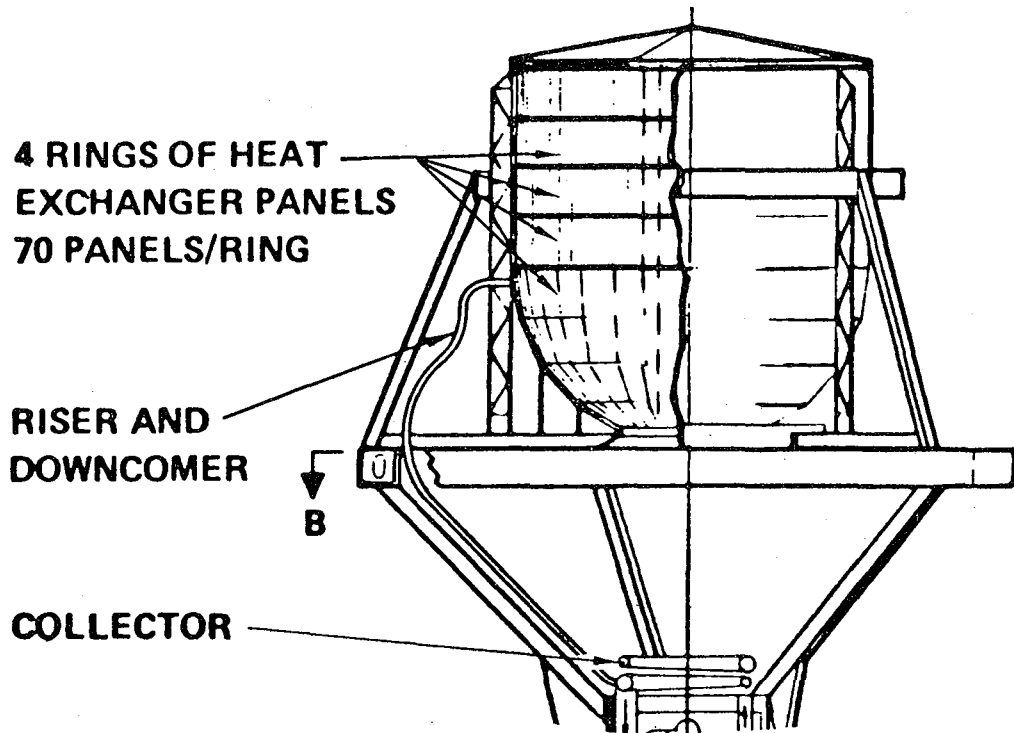
Fig. 2.1. Flowsheet for the daytime (charging) storage process.

Table 2.1. Stream conditions and heat duties for the daytime high-temperature side.

Stream No.	State	Concentration (Mole Fraction)			Temp. (°K)	Pres. (Bar)	Flow (kmol/s)	Enthalpy (MJ/kmol)
		O <sub>2</sub>	SO <sub>2</sub>	SO <sub>3</sub>				
1	l	0.00	0.07	0.93	362.	11.0	1.03	-30.02
2	l	0.00	0.03	0.97	375.	40.0	2.69	-28.00
3	l	0.00	0.03	0.97	443.	40.0	2.69	-11.13
4	g	0.00	0.03	0.97	443.	40.0	2.69	8.26
5	g	0.00	0.03	0.97	1007.	40.0	2.69	49.48
6	g	0.15	0.33	0.52	1148.	40.0	3.16	50.28
7	g	0.15	0.32	0.53	593.	40.0	3.16	15.24
8	g	0.19	0.36	0.45	418.	40.0	2.47	5.55
9	l	0.00	0.22	0.78	418.	40.0	0.69	-15.00
10	g	0.56	0.30	0.14	379.	40.0	0.85	2.97
11	l	0.00	0.38	0.62	379.	40.0	1.62	-20.96
12	g	0.77	0.20	0.03	343.	40.0	0.62	1.47
13	l	0.00	0.57	0.43	343.	40.0	0.23	-24.12
14	g	0.80	0.18	0.02	333.	40.0	0.59	1.12
15	l	0.00	0.65	0.35	333.	40.0	0.03	-24.12
16	l	0.00	0.36	0.64	391.	40.0	2.57	-18.78
17	l	0.00	0.99	0.01	334.	10.8	0.91	-17.81
18	l	0.00	0.01	0.99	383.	10.8	1.66	-26.63

Heat exchanger loads (MW<sub>t</sub>)

HE-1	110.8
VAP	52.7
PREHEATER	44.9
REBOILER	45.2
STEAM REBOILER	11.3
BFW	1.6
TRIM	6.5
DIST. COND.	57.0



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Fig. 2.2. Boeing solar receiver (Ref. 5).

3) The Condensers: The main function of the condensers is to separate noncondensable oxygen from the liquid  $\text{SO}_2$  and  $\text{SO}_3$  before feeding the process stream to the distillation column. The heat of condensation is used to preheat liquid  $\text{SO}_3$  feed and boiler feedwater and also to supply part of the reboiler duty for the distillation column.

4) The Distillation Column: Conversion of  $\text{SO}_3$  in the high-temperature reactor is limited by equilibrium to 46.6% at the temperature and pressure proposed. The distillation column, operating at 11 atmospheres, separates  $\text{SO}_2$  from the unreacted  $\text{SO}_3$ . The  $\text{SO}_2$  is stored at near ambient temperature, while  $\text{SO}_3$  is recycled to the high-temperature reactor.

5)  $\text{SO}_3$  Vaporizer: This is the second largest source of heat input into the storage system (the solar collector is the largest). Steam is taken from the parallel solar power plant to vaporize the liquid  $\text{SO}_3$ .

6) The Parallel Power Plant (not shown in Fig. 2.1): While the storage system is charging, steam is also being generated in the receiver to produce power. Steam at intermediate pressure is taken from this plant to vaporize the liquid  $\text{SO}_3$  and, if necessary, supply part of the heat required by the distillation column reboiler.

#### B. Detailed Design Considerations

Computer programs simulating the reactor, distillation column, and other components were integrated into one overall program for the entire system. Flow charts and a complete program listing are given in Appendix C. This program was used to determine heat duties for the various units, as

well as to predict the effects of changing various design parameters. The design presented here evolved from several such calculations.

1. The Receiver. The receiver configuration utilized in this system is that proposed by Boeing (Fig. 2.3) [5] and is used here only to establish that tube wall temperatures and receiver temperatures are technically feasible. The receiver is situated at the top of a supporting tower 300 meters tall. This tower is located about in the middle of a more-or-less elliptically shaped mirror field. The tower is located to the south of the major axis of the ellipse because the sun does not pass directly overhead in non-tropical latitudes.

The mirrors reflect sunlight into the receiver through the aperture at the bottom. Incident energy is absorbed by the refractory brick lining the lower portion of the cavity, and is re-radiated to tubes located in the upper portion. This indirect transfer of heat reduces the possibility of hot spots occurring in the tubes. If the focused sunlight were directly incident upon the tubes, hot spots would be inevitable as a result of improper mirror aim.

In the Boeing design the heat exchanger tubes are arranged in four rows of 70 panels per row. Each panel consists of two offset columns of heat exchanger tubing (Fig. 2.4); there are 20 tubes on a panel, each tube having a total length of 9.5 meters. Each tube makes two passes: one from the inlet down to the bend, and a second pass close to the cavity insulation up to the outlet. The difference in path length is to provide proper tube expansion during thermal cycling.

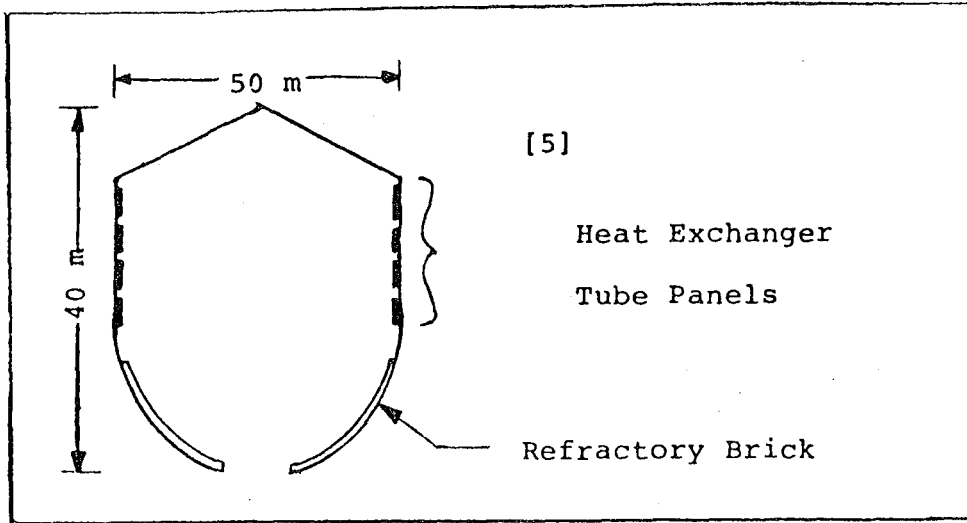
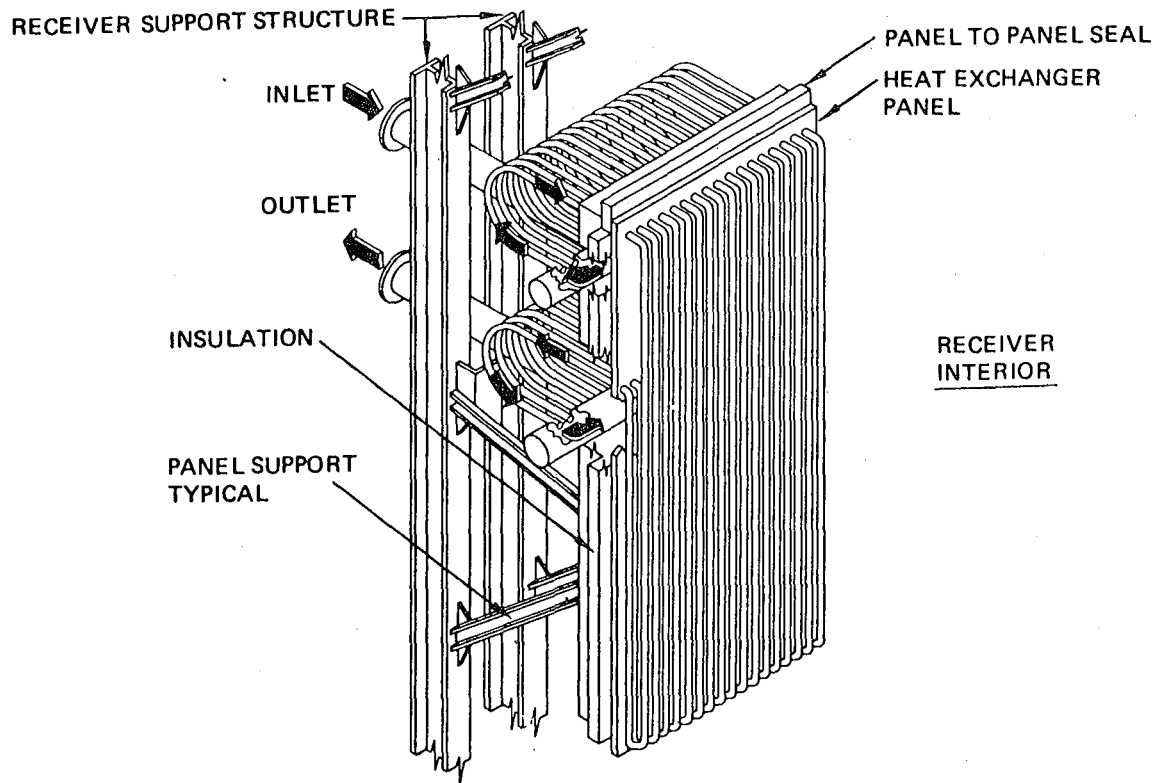


Fig. 2.3. Location of tube banks in Boeing solar receiver.



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Fig. 2.4. Heat exchanger tube panel (Ref. 5).

The Boeing design is capable of absorbing  $230 \text{ MW}_t$  and contains 5600 tubes. The present design for the base case calls for using 800 of the receiver tubes for the power plant and 4800 of them for the storage reactor in which  $\text{SO}_3$  is dissociated. The power-plant tubes are subdivided to provide for boiling (460), superheating (240), and reheating. The storage-reactor tubes are connected to form 2400 pairs, each pair making a tube with an equivalent length of 19 m. This division of receiver tubes between power-plant duty and storage-reactor duty, 1 to 6, results in a ratio of solar heat input to the two systems of 1.05 to 1. The radiative thermal flux to the reactor tubes is much lower than that to the power plant tubes because the former operate at a much higher temperature than the latter.

The tubes are made of Haynes 188 alloy for reasons discussed in Chapter VI. The reactor tubes are coated on the inside with the  $\text{Fe}_2\text{O}_3$  catalyst, and thus provide both heat-transfer area and catalyst support. Because the reaction occurs on the inner surface of the tube, heat-transfer resistance is minimal, mass-transfer resistance is significant. However, the primary factor controlling the fraction of  $\text{SO}_3$  that can be dissociated is the maximum allowable tube-wall temperature, which is limited by the physical properties of Haynes 188 alloy.

Many simplifying assumptions were made during the computer modeling of the high-temperature reactor and are stated below. These assumptions may be eliminated as need for greater accuracy in calculations stimulates further work on the reactor design.

a. The model used for the reactor was a simple one-dimensional plug-flow model. Radial gradients in bulk temperature and concentration were



ignored, as was axial diffusion. The high linear gas velocity (3 meters per second) and the high length-to-diameter ratio of the tubes indicates that the assumption is not too far removed from reality.

b. The reaction mixture at the tube wall was assumed to be at equilibrium. The reaction rate is limited by the turbulent convection of  $\text{SO}_2$  away from the wall and into the bulk. This is an important assumption that finds some support in the results of experiments described in Chapter V.

c. The radiative source (refractory brick) temperature was assumed to be constant throughout the collector, and the heat flux through the tube walls was calculated using the usual fourth-power radiant heat-transfer relationship for black bodies. No attempt was made to calculate a shape factor or source temperature distribution.

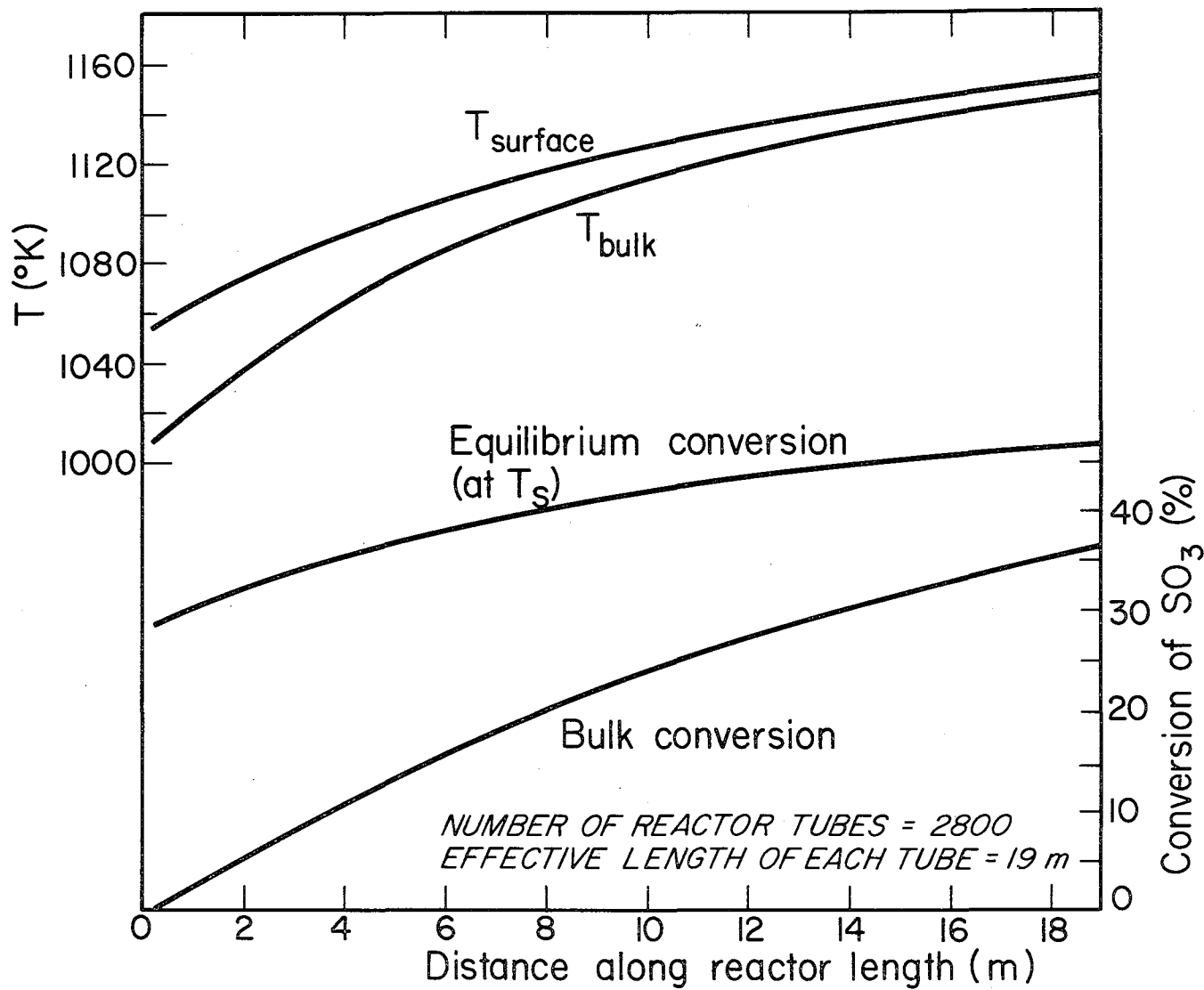
d. The effect of re-radiation from the reactor tubes to the nearby colder steam boiler and superheater tubes was ignored. The tubes used for steam are identical to the ones that carry the sulfur oxides. The maximum outside wall temperature of the reactor tube wall is  $880^\circ\text{C}$ . The maximum outside tube wall temperature for the boiler, superheater and reheater are  $380^\circ\text{C}$ ,  $570^\circ\text{C}$  and  $570^\circ\text{C}$  respectively. These temperatures are based upon the heat flux required to heat the steam, and upon the radiant heat-transfer relation mentioned above. The tubes can withstand a maximum operating temperature of  $880^\circ\text{C}$  based upon stress-rupture properties of Haynes 188 alloy.

A summary of experimental evidence that  $\text{Fe}_2\text{O}_3$  catalyzes the dissociation of  $\text{SO}_3$  is given in Chapter V. Considerations in the relation of materials of construction and specification of the maximum temperature

of the receiver tubes are summarized in Chapter VI. The reactor model equations, parameters, and method of calculation are given in Appendix A; the computer program is in Appendix C.

The temperatures of the inside tube surface and of the bulk gas are plotted against reactor length in Figure 2.5 for the base case. Also plotted is the degree of conversion at the tube surface and in the bulk gas. In the base case the inlet bulk temperature and the maximum tube wall temperature were 730°C and 880°C, respectively. The amount of heat absorbed by the sulfur oxide stream was 112 MW<sub>t</sub>. It will be noted that the equilibrium SO<sub>3</sub> conversion, at the inner tube surface near the reactor inlet, is significantly greater than the conversion of SO<sub>3</sub> in the bulk gas leaving the reactor. Greater conversion of the bulk gas could be obtained if a higher tube wall temperature were permissible. Alternatively, it could also be obtained by increasing the effective tube length (having more than two tubes in series) if the total radiation flux were decreased to avoid exceeding the maximum tube-wall temperature. The effect of the former approach is discussed in Chapter VIII.

2. Heat Exchanger 1. In this heat exchanger, high-temperature gas exiting from the receiver/reactor gives up heat to the incoming reactor feed gas. The area required for the heat exchanger is determined by the temperature difference ( $\Delta T_{5-6}$ ) between the two streams. In the base case this was set at 140°C. In Chapter VIII of the report, effects of changes in this temperature difference are studied. The temperature of the SO<sub>3</sub> entering HE-1 from the vaporizer, T<sub>4</sub>, is set by the pressure of the system; it is the boiling point of liquid SO<sub>3</sub> at 40 atmospheres.



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Fig. 2.5. Temperature and conversion profiles along the reactor tubes.

The stream from the reactor leaves the exchanger at  $T_7$ , set by a heat balance around HE-1.

3. The Condensers: Condenser 1. The inlet temperature of the cool stream ( $T_2$ ) is known from the  $\text{SO}_3$  storage temperature and the temperature of the  $\text{SO}_3$  recycle stream. The inlet temperature of the hot stream,  $T_7$ , is known from the HE-1 calculation. Thus the enthalpy, temperature, and the vapor/liquid split of the exit stream from the condenser may be calculated, using conventional condenser calculation techniques.

4. Reboiler. The gas stream from Condenser 1 flows through one side of this condenser. The other side acts as the reboiler for the  $\text{SO}_3$ - $\text{SO}_2$  distillation column. The exit temperature for the condensing side is set by the temperature approach ( $10^\circ\text{C}$ ) in the reboiler of the distillation column. This in turn sets the exit enthalpy and the vapor-liquid split for the condensing side. When the reboiler load exceeds the heat available in the process stream, the deficit is supplied by steam extracted from the turbines and fed to the make-up reboiler.

5. Boiler Feed Water Heater. This condenser supplies some of the heat required to preheat boiler feed water for the daytime power system. The rest of the heat must come from turbine steam extraction. The heat available in this unit, limited by the  $10^\circ\text{C}$  temperature approach, determines the ratio of power-to-storage heat input (see Chapter VII).

6. Trimmer. The system rejects some heat to the atmosphere through this cooler-condenser. The separation between oxygen and liquid sulfur oxides is completed here. Gas exiting from this unit goes to oxygen storage.

7. The Distillation Column. Liquids exiting from all four condensers are introduced into the distillation column. The column pressure is set at 10.8 atmospheres to allow condensation of the distillate at 60°C, the heat discharge temperature set for the base case. The liquid feed will partially flash when introduced. SO<sub>3</sub> (99% pure) leaves from the bottom and is recycled back to the high-temperature reactor. The distillate (99% pure SO<sub>2</sub>) leaves from the top, going to the liquid-SO<sub>2</sub> storage vessels. The reflux rate was selected empirically because the operating lines are curved. Tray-to-tray calculations accounting for changes in the heat of vaporization confirmed the adequacy of this choice and showed that sufficient reflux was available to yield a normal pinch near the feedtray. The minimum reboiler heat duty was based on this reflux rate. Raoult's Law was used to calculate the vapor-liquid equilibria.

8. Make-up Reboiler. Additional heat for the reboiler is supplied by steam taken from the power system turbines and fed to this unit. It is desirable to minimize the steam extraction from the power system because the steam could be used to generate electricity. Storage-system designs that minimize the heat load on this unit and on the SO<sub>3</sub> vaporizer are preferable.

9. SO<sub>3</sub> Vaporizer. The SO<sub>3</sub> vaporizer uses heat from the parallel power plant, in the form of extraction steam, to convert the liquid SO<sub>3</sub> feed to the gas phase. There is no process stream with enough enthalpy, and at a high enough temperature, to vaporize all of the SO<sub>3</sub>. Steam taken from the discharge of the intermediate-pressure turbines condenses at a convenient temperature for this purpose:

1840C, or approximately 120C higher than the boiling point of the SO<sub>3</sub> stream. Hence SO<sub>3</sub> is vaporized by steam that has already performed work in the high- and intermediate-pressure turbines.

10. The Parallel Power Plant. This plant utilizes steam produced in the solar collector during the eight daylight hours. The turbine and steam cycle used are described in the next chapter, under "Electricity Generating System."

### III. NIGHTTIME OPERATION: The Discharging System

#### A. General Description of Process

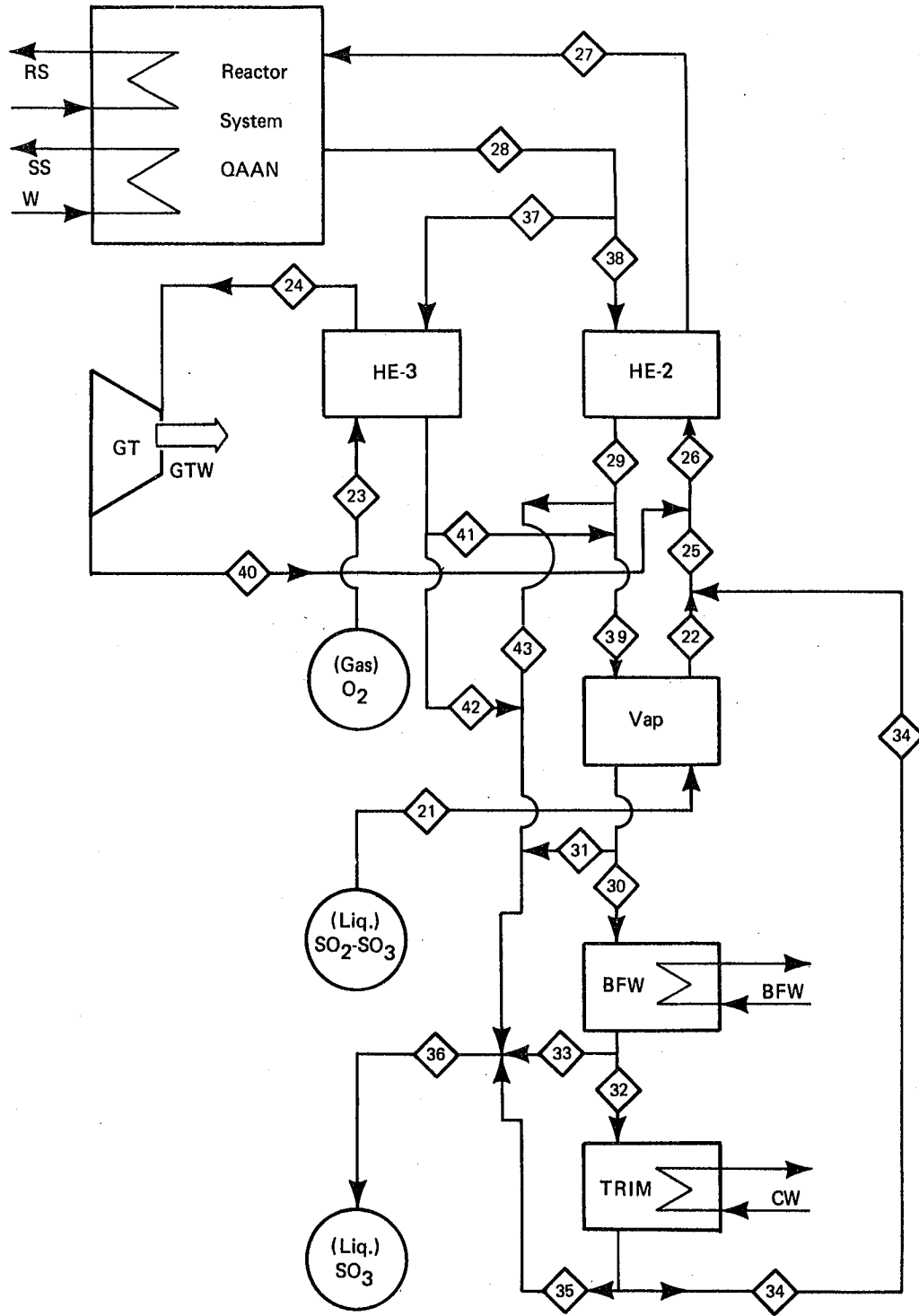
A detailed flow sheet for the low-temperature side, or discharging side, of the process is presented in Figures 3.1 and 3.2. Tables 3.1 and 3.2 give the stream conditions for the base case. The major process components are:

1) The Low-Temperature Reactors (LTR's): These five reactors are adiabatic beds packed with a supported  $V_2O_5$  (vanadium pentoxide) catalyst, each followed by an adiabatic bed packed with a platinum catalyst. The reasons for this dual-bed design are detailed below.

2) LTR Heat Exchangers: The LTR heat exchangers are used to boil water and generate superheated steam at 144 atmospheres (2116 psi) and 35 atmospheres (510 psi), both at 538°C (1000°F). They have been arranged to obtain maximum steam generation per unit gas flow (0.354 kg of high-pressure steam per kg of  $SO_2-O_2$  mixture processed), with a minimum of heat exchange area.

3) Electricity Generating System: A General Electric turbine design for high-back-pressure turbines has been modified for this system. The most important modification is the replacement of some steam extractions used for boiler feedwater preheat by process heat exchangers. The amount of steam fed to the low pressure turbines is thereby raised, increasing electricity production.

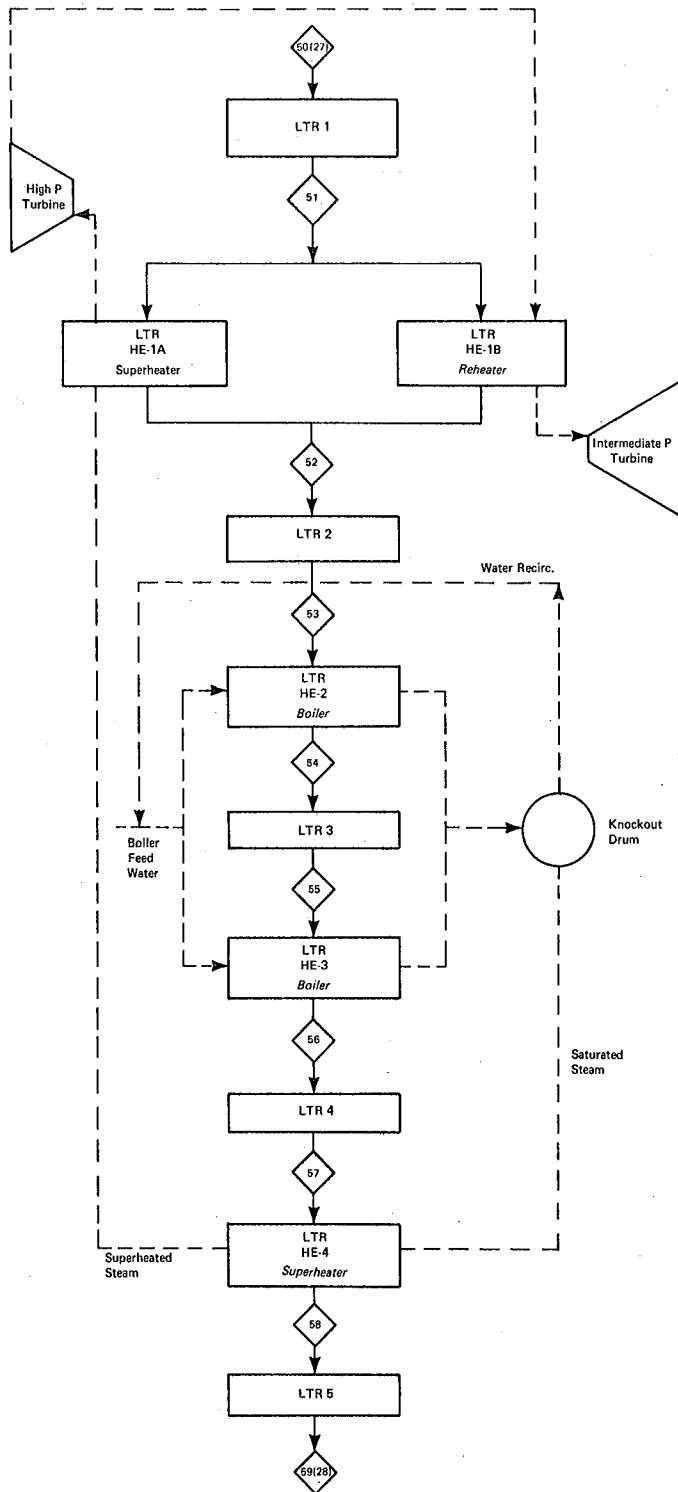
4) Heat Economizers: These units preheat boiler feedwater. They also preheat low-temperature reactor feed to the necessary ignition temperature of 420°C.



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Fig. 3.1. Flowsheet for the nighttime (discharge process).





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Fig. 3.2. Low temperature reactor/heat exchange series.

Table 3.1. Stream conditions and heat duties for the nighttime operation of the low temperature side.

Stream No.	State	Concentration (mole fraction)			Temp. (°K)	Pressure (Bar)	Flow (kmol/s)	Enthalpy (MJ/kmol)
		O <sub>2</sub>	SO <sub>2</sub>	SO <sub>3</sub>				
21	l	0.00	0.99	0.01	333.7	11.0	0.46	-17.81
22	g	0.00	0.99	0.01	333.7	11.0	0.46	1.46
23	g	0.80	0.18	0.02	333.0	40.0	0.29	1.12
24	g	0.80	0.18	0.02	573.0	40.0	0.29	9.30
25	g	0.01	0.99	0.01	333.7	11.0	0.46	1.46
26	g	0.32	0.67	0.01	354.7	11.0	0.76	2.14
27	g	0.32	0.67	0.01	693.0	11.0	0.76	16.37
28	g	0.01	0.07	0.93	777.1	11.0	0.52	30.95
29	g	0.01	0.07	0.93	400.8	11.0	0.42	5.62
30	g	0.01	0.09	0.89	382.0	11.0	0.28	4.48
31	l	0.00	0.03	0.97	382.0	11.0	0.24	-26.57
32	g	0.02	0.11	0.87	381.3	11.0	0.22	4.41
33	l	0.00	0.04	0.96	381.3	11.0	0.06	-26.61
34	g	0.71	0.11	0.18	333.0	11.0	0.01	1.22
35	l	0.00	0.11	0.89	333.0	11.0	0.21	-34.82
36	l	0.00	0.07	0.93	361.7	11.0	0.52	-30.18
37	g	0.01	0.07	0.93	777.1	11.0	0.10	30.95
38	g	0.01	0.07	0.93	777.1	11.0	0.42	30.95
39	g	0.01	0.07	0.93	400.8	11.0	0.52	5.62
40	g	0.80	0.18	0.02	396.2	11.0	0.29	3.20
41	g	0.01	0.07	0.93	400.8	11.0	0.10	5.62

Heat Exchanger Loads (MW<sub>t</sub>)

HE-2	2.41	BWF	1.83
HE-3	10.76	Trimmer	8.36
Vaporizer	8.81	QAAN (heat available at night)	40.34
		Gas Turbine Work	1.80

Table 3.2. Stream conditions, heat loads, and conversion for the low-temperature reactor system.

Stream No.	Concentration (mole fraction)			Temp. (°K)	Pressure (Bar)	Flow (kmol/s)	Reactor System (MJ/kmol)
	O <sub>2</sub>	SO <sub>2</sub>	SO <sub>3</sub>				
50	0.32	0.67	0.01	693.0	11.0	0.76	16.37
51	0.22	0.48	0.29	1150.3	11.0	0.66	44.83
52	0.22	0.48	0.29	693.0	11.0	0.66	18.98
53	0.13	0.31	0.55	1016.3	11.0	0.60	42.06
54	0.13	0.31	0.55	693.0	11.0	0.60	21.36
55	0.06	0.17	0.76	912.2	11.0	0.55	38.59
56	0.06	0.17	0.76	693.0	11.0	0.55	22.32
57	0.02	0.09	0.90	815.4	11.0	0.53	33.43
58	0.02	0.09	0.90	752.3	11.0	0.53	28.80
59	0.01	0.07	0.93	777.1	11.0	0.52	30.95

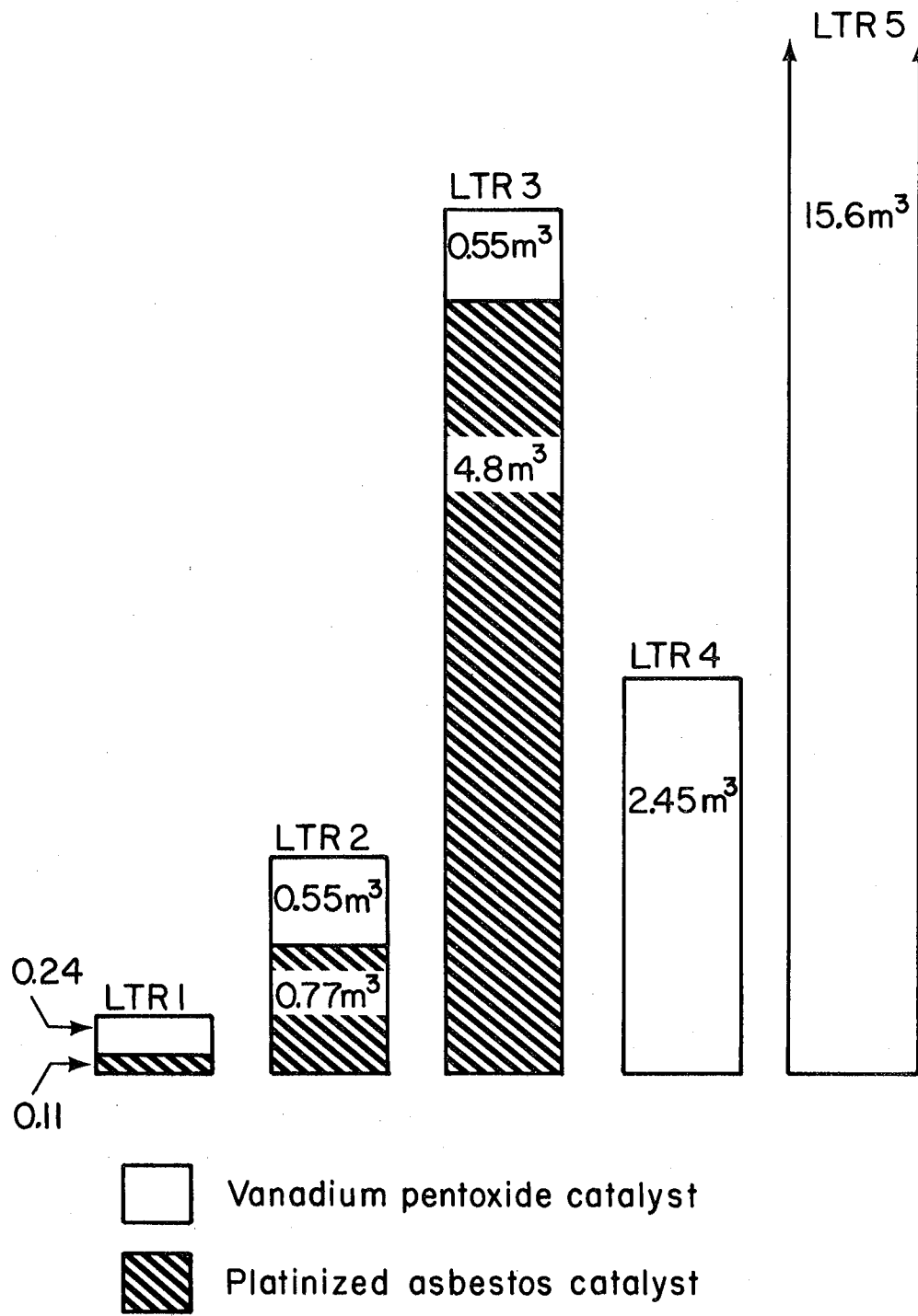
Heat Exchanger Loads (MW <sub>t</sub> )		Reactor Conversions	
		$\frac{\text{moles SO}_2 \text{ Converted}}{\text{moles SO}_2 \text{ fed}}$	
HE-1	17.16	LTR-1	0.367
HE-2	12.34	LTR-2	0.418
HE-3	8.41	LTR-3	0.489
HE-4	<u>2.43</u>	LTR-4	0.531
		LTR-5	0.233
TOTAL	40.34	Total System Conversion = 0.932	

## B. Detailed Design Considerations

1. The Low-Temperature Reactors: Non-adiabatic reactors were considered before the decision to use adiabatic reactors was reached. Computer simulations showed, however, that the reaction was so fast, and heat transfer was so limited, that the system reached equilibrium conversion at a very small bed depth; the reaction occurred almost adiabatically anyway. The reaction remained at equilibrium, temperature slowly dropping and conversion slowly increasing as heat was withdrawn. Because of this behavior, it seemed much more economical to use short reactor beds followed by heat exchangers, avoiding the problems associated with packed beds with tubes imbedded in them and decreasing the reactor volume and amount of catalyst required.

Each reactor actually consists of two reactors in series. The reason for this is the need to protect the  $V_2O_5$  catalyst from thermal degradation. The first reactor is a very short bed of the vanadium catalyst, for which the exit temperature is  $600^\circ\text{C}$ , and precedes a second bed of the high-temperature platinum catalyst, in which the reaction mixture achieves a 99% approach to equilibrium. Catalyst distributions are shown in Figure 3.3. The need for a platinum catalyst may be obviated, however, if the reactor feed contains appreciable amounts of  $\text{SO}_3$ , as would be the case were the distillation column not a part of the charging process. This process modification is discussed in Chapter VIII.

Platinum alone is not acceptable as a catalyst. The catalytic mechanism over Pt involves adsorption of the reactants, and this step is strongly temperature dependent [14,27]. Platinum gives an acceptable reaction rate only above  $550^\circ\text{C}$ .



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Fig. 3.3. Volume of low temperature reactor beds.

The vanadium beds were designed to achieve a temperature of 600°C, the maximum temperature for steady-state operation. The catalyst can withstand temperatures as high as 620°C for a short time. Thus there is some margin of safety: if the bed exit temperature exceeds 600°C, the bed inlet temperature may be decreased or the gas flow rate increased to return the exit temperature to the design point.

The platinum beds were designed for an inlet temperature of 550°C. This, too, includes a margin of safety. Fluctuations in flow rates and decline of the vanadium's activity with time may cause the temperature of the gas exiting from the vanadium bed to drop below 600°C. As long as the outlet temperature from the vanadium bed remains above 550°C, the length of the platinum bed is sufficient to achieve the designed level of final conversion. Reactors 4 and 5 never achieve a temperature of 600°C. Each consists, therefore, of only a single  $V_2O_5$  packed bed; the high-temperature platinum beds are not required.

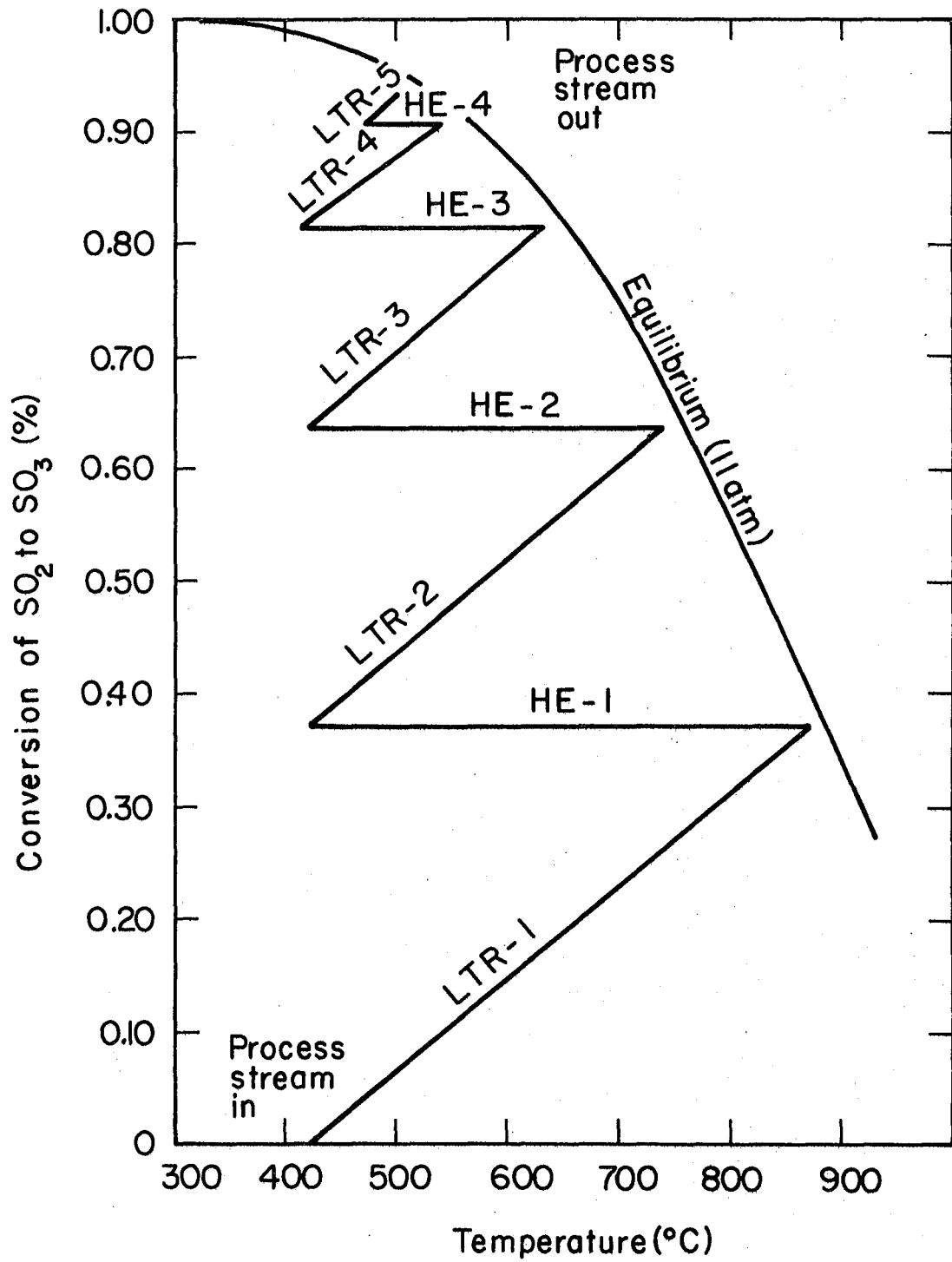
A computer program described in Appendix B has been developed in the course of this work to simulate a reactor bed packed with the vanadium catalyst. The most basic assumption of this program is that the kinetics, rather than heat and mass transfer, limit the reaction rate. The results indicate that such a bed achieves the ceiling temperature of 600°C very rapidly. The vanadium beds of Reactors 1, 2 and 3 are very short as a result. The total volume of  $V_2O_5$  bed was estimated to be 0.84 m<sup>3</sup> per kg/sec of  $SO_2-O_2$  mixture fed to the reactor sequence. This volume is based on a catalyst density of 680 kg/m<sup>3</sup>. The actual volume may vary with catalyst density and approach to equilibrium, but these parameters have insignificant effect on total system cost.

2. LTR Heat Exchangers: LTR Heat Exchangers 1, 2, 3 and 4 perform the same functions that furnace boiler and superheater tubes serve in a conventional steam plant. The relative loads on the boiler, superheater, and reheater are fixed by the selection of turbine operation conditions.

All of the vapor generated by the boiler goes to the superheater. The amount of heat required to take the saturated vapor to the turbine inlet conditions is supplied in HE 4 and HE 1A.

The power system design calls for steam extractions between the various turbine stages to supply the additional heat required to preheat all of the boiler feedwater. Of the steam exiting from the high pressure turbine, 9.6% is extracted for this purpose. The flow rate within the steam reheater and the intermediate turbine is decreased to 89.8% of the flow through the superheater and the balance, 0.8%, is lost through seal leaks. Likewise, the flow rate through the low pressure turbine is reduced to 79% of the superheater flow. The ratios of the heat duties in the boiler, superheater, and reheater are 1.00/ 0.515/0.230.

The reactor/heat exchanger series may be designed graphically on a conversion-temperature diagram as shown in Figure 3.4. The heat exchanger duty is directly proportional to the length of the horizontal line representing it through the equation  $Q=FC_p \Delta T$ . Hence the reactor design consists of drawing diagonal lines representing the adiabatic reactors (the slope of these lines corresponds to the particular value of  $-Cp/\Delta H_R$  at this reactor) and horizontal lines representing heat exchangers. The outlet temperatures of all the streams exiting the five reactors is determined by the reaction equilibrium. The first three streams are cooled in their respective heat exchangers to



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Fig. 3.4. Conversion and temperature changes in the low temperature reactor system.

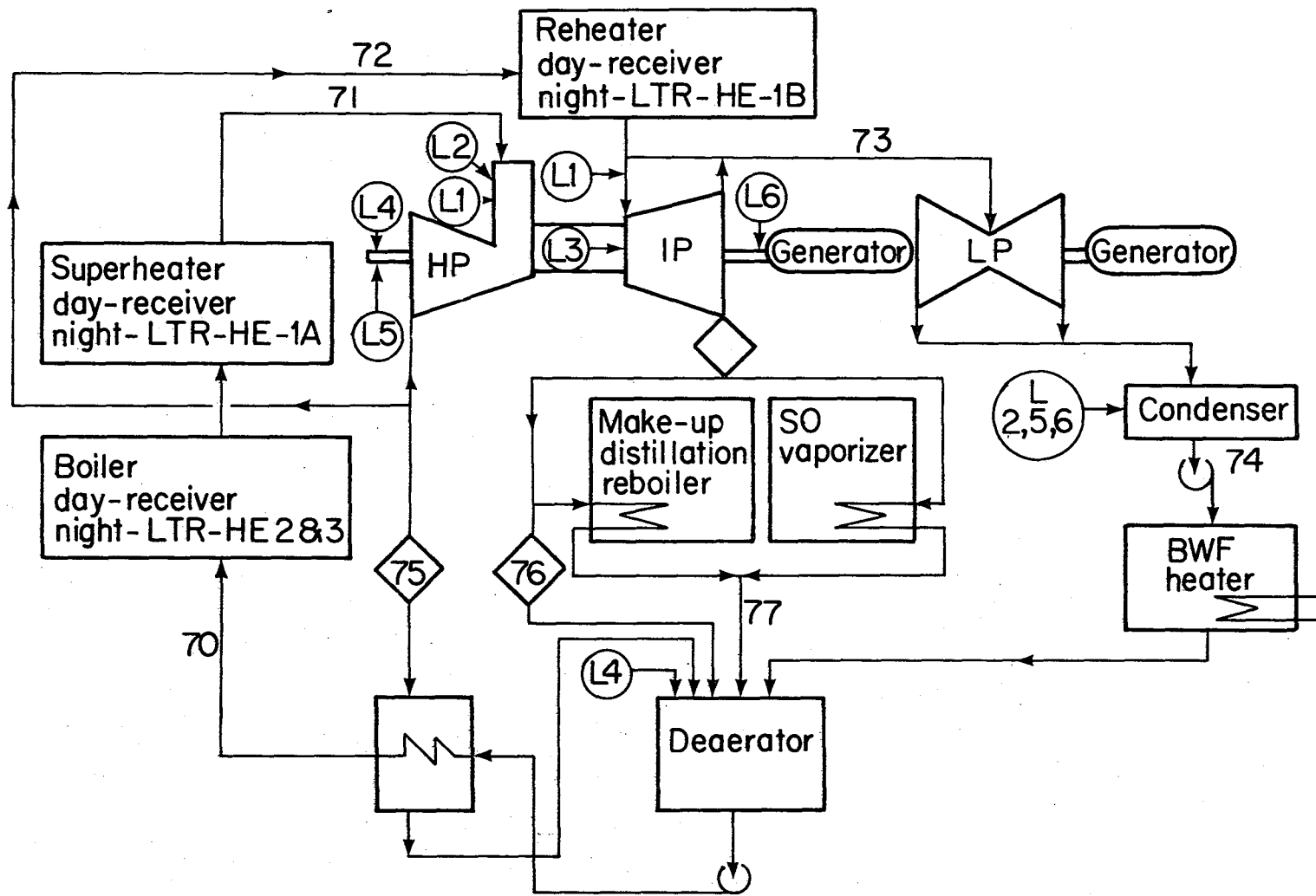


420°C. The fourth reactor exit stream, which is the inlet to the fifth reactor, is cooled to 474°C, a temperature selected so that the effluent temperature of Reactor 5 would be 500°C.

3. Electricity Generating System (Steam Turbines): A General Electric system designed for high back pressure [33] has been modified to meet the requirements of this system. The configuration is shown in Figure 3.5; stream conditions are given in Table 3.3. Stream conditions are essentially those of the G. E. design. Flows were determined from those of the G. E. design by ratio of the electric power produced in this application to that of the G. E. design.

Some of the boiler feedwater preheat necessary at night is provided by condensing  $\text{SO}_3$  in the BFW heater (Figure 3.1). The rest is provided by steam extraction from the high and intermediate pressure turbines (Figure 3.5).

Design of the steam turbine system for the power plant is dependent on the rate at which the storage system is to be discharged and the strategy that is adopted for keeping the turbine system in standby condition when the rate of power generation is low. The amount of energy stored in the base case studied here is about 808  $\text{MW}_t\text{-hr}$  after 8 hours of daytime operation. This is enough to operate the daytime steam turbine system at its rated capacity of 30.9  $\text{MW}_e$  for only about 8 hours. Since operation of a steam turbine at a rate of about 50% of design capacity results in a substantial drop in efficiency, the choice of discharge program will affect the equivalent amount of electric storage materially.



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Fig. 3.5. Steam power cycle.

Table 3.3. Flows and stream conditions in steam power cycle.

Stream No.	Flow Rate, 10 <sup>3</sup> lb/hr			Temp., °F	Pressure, psia	Enthalpy Btu/lb
	Daytime	Nighttime				
		Large Turbine	Small Turbine			
70	335	5.9	108.8	455	494	457
71	335	5.9	108.8	1000	1800	1480
72	297	5.2	96.5	1000	459	1521
73	83	4.6	85.6	736	158	1394
74	84	4.6	86.0	141	3	109
75	32	0.6	10.5	679	510	1344
76	11	0.6	11.9	736	158	1394
77	206	0	0	363	153	335
Seal Leaks						
L1	0.39	0.01	0.13			
L2	0.1	0.00	0.04			
L3	3.38	0.06	1.10			
L4	1.30	0.02	0.42			
L5	0.47	0.01	0.15			
L6	0.52	0.01	0.17			
Power Generation (MW <sub>e</sub> )						
	30.9	0	15.1			

Another factor of importance is the benefit to be derived by keeping the turbine system hot and turning when it is at standby. If the turbines are not kept hot, a start-up period of about 90 min will be required at the beginning of daytime operation. A flow of steam of about 3.5% of design rate was assumed to be required to keep a turbine in hot standby condition.

The strategy that was chosen here was to design a dual daytime steam turbine system, each having about the same electrical capacity. One would consist of a conventional set of high-, intermediate-, and low-pressure turbines and would operate with about one-third of the total steam flow during the day. The other would consist only of the high- and intermediate-pressure turbines. The steam discharged from this set, about two-thirds of the daytime total, is required for the vaporizer and reboiler in the storage system. This design results in a ratio of solar heat inputs to the power plant and storage receivers of 1.05.

During nighttime operation the conventional turbine system would be operated at its rated capacity for the entire night by steam generated from the storage system. The other turbine system would be kept on hot stand-by. This design strategy would result in the maximum generating efficiency for the base case. However, a different splitting of capacities might be chosen if it were preferable to discharge the storage system at a higher rate for part of the discharge period.

4. Heat Economizers (Vaporizer, HE-2, HE-3). These units make as much use of process heat as possible. They preheat boiler feedwater, preheat reaction feed, and vaporize  $\text{SO}_2$  by exchanging heat with the  $\text{SO}_3$  stream coming out of LTR 5 at  $500^\circ\text{C}$ . The heat exchangers have been

arranged so that the temperatures that the  $\text{SO}_3$  stream first encounters in each economizer are always decreasing.

#### IV. STORAGE VESSELS

One problem associated with large-scale energy storage of any type is the enormous mass of storage medium that is required. Chemical storage presents several potential advantages over other systems, but perhaps the most important is the potential for less mass that must be stored [4].

In the sulfur oxide system a nighttime discharge of 15.1 MW<sub>e</sub> lasting 16 hours (790 MW<sub>t</sub>-hours storage) requires storage of 1704 x 10<sup>3</sup> kg of SO<sub>2</sub> and 636 x 10<sup>3</sup> kg of O<sub>2</sub>. (This O<sub>2</sub> also contains 18% SO<sub>2</sub> and 2% SO<sub>3</sub>) It requires daytime storage of 2370 x 10<sup>3</sup> kg of SO<sub>3</sub>.

Sulfur dioxide and SO<sub>3</sub> are storable as liquids at ambient temperature. The storage volume for the amount of reactants indicated above is 1290 m<sup>3</sup> (SO<sub>3</sub> density at 38°C is 1.843 g/cm<sup>3</sup>; thermal expansion of the liquid is neglected). Liquid SO<sub>2</sub> has a density of 1.356 g/cm<sup>3</sup>, giving an SO<sub>2</sub> storage volume of 1260 m<sup>3</sup>.

It has been suggested that joint storage of SO<sub>2</sub> and SO<sub>3</sub>, using the same storage vessels for both, be utilized [5]. The basis for this suggestion is the fact that SO<sub>2</sub> and SO<sub>3</sub> need not be stored simultaneously; the same storage volume may be used for both. A joint storage system would be modular, as shown in Figure 4.1. One tank would be in the process of filling as another was being emptied. One disadvantage to this system would be the necessity of a complex manifold to distribute and collect the SO<sub>x</sub> streams. Another apparent disadvantage is that of contamination. Neither stream, however, is expected to be chemically pure. Contamination by liquid adhering to storage tank walls will not be significant when compared to that caused by incomplete separation in the distillation column.

Oxygen must be stored as a gas. The pressure of oxygen storage should be optimized, playing the capital cost of high storage volume against the energy cost of compressing oxygen to a high pressure, plus the energy cost of reheating the oxygen when it expands to system pressure.

In this design the pumping of gases has been totally avoided. All pumping is done on liquids, with great savings in energy consumption. The pressure used for oxygen storage, therefore, will be the daytime operating pressure of 40 atmospheres.

At 40 atmospheres and 60°C, the storage volume for  $636 \times 10^3$  kg of  $O_2$  is  $11,280 \text{ m}^3$ . This is the volume of accessible oxygen that must be provided. A holdover volume of  $11/40$  times the total volume must also be provided if no pumping is to be done. Finally, additional storage volume is required because of the  $SO_2$  and  $SO_3$  content. Thus a total gas storage volume of  $14,420 \text{ m}^3$  is required, and provision must be made for removing  $SO_2$  liquid that may condense during storage.

A possible alternative to steel pressure vessels for storing oxygen is cavern storage. A large underground cavity is excavated and lined with steel to prevent leakage. The cavity is constructed at a depth of approximately 300 m. The depth is chosen so that the surrounding rock takes up all of the pressure in the system. The lining serves only to prevent contact between the gas and the rock.

It is difficult to evaluate the economy of this method of storage in this application. Cost estimates of between 5 and 25 dollars per cubic yard have been reported [30]; others range up to 300 dollars per cubic yard [22]. This last cost is still less than the cost of

above-ground steel pressures vessels for the oxygen storage; thus it seems that cavern storage is a definite possibility in this case. More accurate estimates should be obtained in any continued investigation of this system.

Cavern storage becomes economical only for large volumes, and thus will not be economical for storage of the liquid  $\text{SO}_2$  and  $\text{SO}_3$ . The volumes involved in storing these liquids are relatively small. Above-ground tank storage seems indicated for storage of these reactants.

Table 4.1 summarizes the information presented in this chapter.

Table 4.1 Reactant Storage

Reactant	Mass Stored	Volume Stored	Pressure	Method of Storage
$\text{SO}_3$	$2370 \times 10^3$ kg	$1,290 \text{ m}^3$	11 atm	mild steel vessel
$\text{SO}_2$	$1704 \times 10^3$ kg	$1,260 \text{ m}^3$	11 atm	mild steel vessel
$\text{O}_2$	$636 \times 10^3$ kg	$14,400 \text{ m}^3$	40 atm	underground cavern, steel lined



## V. CATALYST EVALUATION

In this storage process,  $\text{SO}_3$  dissociates at temperatures in excess of  $700^\circ\text{C}$ , and  $\text{SO}_2$  and  $\text{O}_2$  recombine at temperatures between about  $400^\circ\text{C}$  and  $700^\circ\text{C}$ . In both cases catalysis is required. Hill [14] has studied part of the extensive literature on the latter reaction, which is practiced industrially in the manufacture of sulfuric acid. Vanadium pentoxide is used below  $600^\circ\text{C}$ , platinum above. The kinetics of the reaction over both catalysts has been investigated. Hill used the results reported to size his heat-release reactors. The following literature references are cited in this thesis [7,11-13,15,16,18,28,32].

The dissociation of  $\text{SO}_3$  is not practiced commercially. However, on thermodynamic grounds one would predict that a catalyst for the recombination reaction would also catalyze the dissociation. The only questionable aspect of this assumption would arise if the catalyst's physical characteristics were adversely affected by the higher temperature.  $\text{V}_2\text{O}_5$ , for instance, becomes appreciably volatile as the temperature approaches  $700^\circ\text{C}$ . Because platinum is expensive, a cheaper alternative would be preferred if it were sufficiently reactive. Iron oxide is a promising candidate because it was used in the now-obsolete Mannheim process. Westinghouse [25] studied the reaction over specular hematite and observed relative low reaction rates. Using pelleted Harshaw catalyst Fe-030IT, a finely divided  $\text{Fe}_2\text{O}_3$  supported on alumina, Hill observed a significant reactivity at temperatures above  $700^\circ\text{C}$ . Hill's work was exploratory in nature and would need to be extended to obtain design data for a reactor.

## VI. MATERIALS OF CONSTRUCTION

Hill [14] searched the literature for promising materials of construction for the reactor tubes within the solar receiver. Useful information was found in Refs. 1-3, 6, 21, 22, 29, 30. He found, as did Boeing [5], that Haynes 188 appears to be the most promising candidate for containing a stream of  $\text{SO}_3$ ,  $\text{SO}_2$ , and  $\text{O}_2$  at a pressure of 40 atm and a temperature of  $880^\circ\text{C}$  on one side and atmospheric air at a similar temperature on the other. The properties cited by Hill are listed below.

Haynes 188, a "superalloy" made by Union Carbide, contains 38% Co, 22% Cr, 22% Ni, and 3% Fe. In addition to having high-temperature tensile strength and oxygen resistance in common with several other alloys, Haynes 188 is expected to be resistant to attack by sulfur compounds to an extent that gives it a significant advantage over its competitors. It should be emphasized, however, that the project reported here did not involve any experimental work with Haynes 188.

## VII. SYSTEM ENERGY ACCOUNTING, EFFICIENCY, AND COSTS

Information derived from the heat and material balances presented in earlier chapters is summarized here to display the important energy flows into, within, and out of the process. The efficiencies of storage and power production are derived from these energy flows. In addition, storage equipment costs are estimated and compared with the costs of other components of the solar power plant.

The calculations presented in this chapter are for the Base Case described in Chapter III. Many of the operating parameters used in this case were chosen rather arbitrarily. In Chapter VIII several of these parameters are varied individually in order to determine the changes in system efficiency and system costs that result.

### A. Energy Accounting

An overall plant energy balance is given in Table 7.1. This energy balance is for the base case outlined in Chapters II and III for the process configuration of Figs. 2.1 and 3.1. The storage process is integrated with the power plant in this flowsheet: extraction steam from one of the power plant turbines is used to heat the reboiler and to vaporize  $\text{SO}_3$ , and low-temperature heat from the storage process is used to preheat boiler feed water during the daytime. The storage system generates steam to run the turbines at night. The relative sizes of the power plant and the storage process are set so that the make-up reboiler and  $\text{SO}_3$  vaporizer completely consume all steam discharging from one of the intermediate-pressure turbines.

From Table 7.1 it is seen that the major energy dissipations to the environment are from the distillation column condenser and the

Table 7.1. Total Plant Energy Balance. Base Case.

	<u>MW (e or t)</u>	<u>MW-hr (e or t)</u>
<b>I. <u>Inputs</u> (8 hours Daytime)</b>		
Power Plant Receiver	117.8 (t)	
Storage Receiver	<u>112.2</u>	
	230.0 (t)	<u>1840.0 (t)</u>
<b>II. <u>Outputs</u></b>		
<b>A. Daytime (8 hours)</b>		
Generator Terminals	30.9 (e)	
Parasitic Power		
BFW Pump	(0.4)	
SO <sub>3</sub> Pump	(0.5)	
Cooling System Power	<u>(0.4)</u>	
Net Power	29.6 (e)	236.8 (e)
Waste Heat		
Trimmer	6.52 (t)	
Dist. Condenser	57.03	
Turbine Steam Leaks	0.40	
LP Turbine Condenser	24.43	
Misc. Heat Losses	5.3	42.5
Total Waste Heat	<u>93.68 (t)</u>	<u>749.5 (t)</u>
<b>B. Nighttime (16 hours)</b>		
Generator Turbine	15.11 (e)	
<small>(small turbine)</small>		
Gas Turbine	.81	
Parasitic Power		
BFW Pump	(0.1)	
SO <sub>2</sub> Pump	(0.2)	
Cool. Syst. Power	<u>(0.1)</u>	
Net Power Prod.	15.5 (e)	248.3 (e)
Waste Heat		
Trimmer	8.36 (t)	
Small Turbine Condenser	24.74	
Large Turbine Bleed	<u>2.10</u>	
Net Night Out	35.20 (t)	563.2 (t)
Misc. Heat Losses	2.66 (t)	42.5 (t)
Total Output		1840.0 (e and t)

power plant condenser during daytime operation and from the trimmer and the power plant condenser during the night. Of these, only the loss from the distillation column can be appreciably affected by process modifications: that step in the process can be eliminated as described in Chapter VIII at the cost of the additional liquid storage required and the larger throughput during discharge of storage.

As noted above, the power plant and the storage process interchange heat at various temperature levels in order to improve the overall thermal efficiency. The heat balance for this storage system is given in Table 7.2. It is seen that there is a large requirement of steam heat to vaporize the  $\text{SO}_3$  but that the boiler water preheat supplied by the storage system is small.

#### B. Efficiency Calculations

Three measures of process efficiency are used in this report to evaluate various aspects of the energy efficiency of the Base Case. These same efficiency indices are used in Chapter VIII to measure the response of the system to variations in several important design parameters. These indices, defined below, represent the overall system efficiency, the efficiency of the daytime power plant, and the efficiency of thermal energy storage. In addition, the ratio of the solar thermal inputs to the daytime power plant and the storage system necessary to minimize energy loss from the total system is an item of interest. The three efficiency indices are  $E_{0A}$ , the overall efficiency;  $E_{pp}$ , the daytime power plant efficiency; and  $E_{TS}$ , the efficiency of thermal storage. The following expressions were used to calculate numerical values for the efficiency indices:

Table 7.2. Storage system energy balance. Base Case.

---

Inputs	MW-hr
Daytime	
Solar Receiver	897.6 (t)
SO <sub>3</sub> Vaporizer	421.2 (t)
Makeup Reboiler	90.1 (t)
Liq. SO <sub>3</sub> Pump	4.0 (e)
Total Input	<u>1412.9</u>
Outputs	
Daytime	
Boiler Feed Preheat	12.5 (t)
Distillation Column	456.2 (t)
Trimmer	52.2 (t)
Daytime Total	<u>520.9</u>
Nighttime	
Boiler Feed Preheat	29.3 (t)
Trimmer	133.7 (t)
LT Reactors (QAAN)	645.4 (t)
Gas Turbine Work (isentropic expansion)	14.4 (e)
Nighttime Total	<u>822.8</u>
Total Output	1343.7

---

$$E_{OA} = \frac{P_{Day} \cdot \theta_{Day} + P_{Sto} \cdot \theta_{sto}}{(Q_{PR} + Q_{SR}) \theta_{Day}}$$

where

$P_{Day}$  = Net power produced by daytime power plant ( $MW_e$ )

$P_{Sto}$  = Net power produced from storage ( $MW_e$ )

$\theta_{Day}$  = Duration of daytime operation (hr)

$\theta_{Sto}$  = Duration of storage discharge operation (hr)

$\theta_{PR}$  = Rate of thermal input to power plant receiver ( $MW_t$ )

$\theta_{SR}$  = Rate of thermal input to storage receiver ( $MW_t$ )

In this simplified expression the thermal inputs and power outputs are assumed constant for the time periods of operation. If these rates are not constant, appropriate integrals would be used.

Low- and intermediate-temperature heat is exchanged between the power plant and the storage system. In discussing the energy efficiencies of the two separately one must therefore arbitrarily "credit" and "debit" the two operations for the heat that is supplied by the one to the other. The power plant efficiency then becomes

$$E_{PP} = \frac{P_{Day} \cdot \theta_{Day}}{(Q_{PP} + Q_{BFW} - Q_{VAP} - Q_{REB}) \theta_{Day}}$$

where

$Q_{BFW}$  = Rate of heat transfer to boiler feed water ( $MW_t$ )

$Q_{VAP}$  = Rate of heat transfer to  $SO_3$  vaporizer ( $MW_t$ )

$Q_{REB}$  = Rate of heat transfer to distillation column reboiler, ( $MW_t$ )

The thermal storage efficiency is defined as the ratio of usable heat delivered by the storage system to the heat input to the storage system

$$E_{TS} = \frac{\sum Q_{Sto} \cdot \theta_{Sto}}{(Q_{SR} + Q_{VAP} + Q_{REB} - Q_{BFW}) \theta_{Day}}$$

where

$\sum Q_{Sto}$  = Sum of rates of heat transfer to power plant system from storage discharge ( $MW_t$ ).

The overall efficiency,  $E_{OA}$ , is simply the second-law efficiency for the total operation, the net total electric energy produced divided by the total thermal energy absorbed by the solar receiver tubes. The definition of  $E_{OA}$  is uncomplicated; however, because it combines the daytime power production with the production from storage, its use does not reveal where losses in efficiency occur. The other efficiencies,  $E_{pp}$  and  $E_{TS}$ , have therefore been defined in a way intended to show the behavior of the separate parts of the integrated operation.

The allocation of energy between the daytime power plant and the storage system is of necessity arbitrary, since the two are integrated to achieve near maximum combined performance. Energy is transferred from the power plant to the storage system by the steam used to vaporize  $SO_3$  and to heat the reboiler. That heat is subtracted from the heat input to the daytime power plant in defining  $E_{pp}$  and is added to the heat input to the storage system in defining  $E_{TS}$ . Conversely, the storage system provides boiler feed water preheat for the power plant both during the day and during the night. Hence the  $Q_{BFW}$  term is added to the heat input to the power plant in defining  $E_{pp}$  and subtracted from



the heat input in defining  $E_{TS}$ . This method of energy allocation tends to make the values of  $E_{PP}$  appear high because the electricity generated by the steam sent to the storage system "costs" the power plant only the enthalpy that is converted into electrical work and not the heat that would normally be discharged to the environment in the power plant condenser.

The thermal storage efficiency,  $E_{TS}$ , represents the fraction of the heat input to the storage system that is released when the storage system is discharged. The steam generated when the storage system is discharged is used in part to generate power and in part to keep some of the daytime turbines on hot standby. The arbitrary distribution between these uses makes it difficult to define a useful index of nighttime power efficiency.

Values of these efficiencies may be calculated from data presented in Tables 7.1 and 7.2.

$$E_{OA} = \frac{(29.6)8 + (15.5)16}{(230)8} = 0.26$$

$$E_{PP} = \frac{(29.6)8}{(117.8)8 + (12.5 - 421 - 90)} = 0.53$$

$$E_{TS} = \frac{645 + 29 + 134}{(112.2)8 - (12.5 - 421 - 90)} = 0.58^*$$

---

\*No credit taken for gas turbine work at night and no debit included for the SO<sub>3</sub> pump during the day. These are small quantities.

The value of  $E_{TS}$  is telltale. Only 58% of the net thermal input to the storage system is actually stored as heat of reaction. The rest is dissipated as unuseable low-temperature heat transferred to the environment. From Table 7.2 it is apparent that most of this loss occurs in the condenser of the distillation column. This relatively low storage efficiency is the principal cause of the low overall efficiency ( $E_{QA} = 0.26\%$ ). If the daytime power plant were operated by itself, its efficiency would be about 40%.

### C. System Costs

Estimates are made here of the cost of installed, functioning equipment; such costs include the cost of connecting process piping, control systems, electrical connections, etc. No plant site auxiliaries such as roads, fences, rail lines, etc. are included. All costs are adjusted to June 1978 by indices published in Chemical Engineering.

Some fabricated equipment costs were determined from the weight of material used and a price stated in \$/kg. The price for fabricated thick-wall pressure vessels made of carbon steel is \$3.20 per kg [7] and 4.25 times this when made of 316 stainless steel [9], or \$13.50 per kg. In these cases, the cost of installation has been taken to be 140% of the fabricated cost [Peters and Timmerhaus, 34]. That is, the cost of in-place equipment is 2.4 times the fabricated equipment cost.

#### 1. The Tower, Receiver, and Mirror Field

The cost of these items is probably the greatest source of uncertainty in the entire design. Nothing even remotely resembling the equipment used in this design has ever been built on this scale.

The cost of these items is not important, however, in choosing between alternative solar storage system designs; almost all proposed designs may be assumed to have the same tower costs per unit of heat absorbed by the storage system. Estimated costs are reported here for the purpose of placing the storage system in perspective.

The Boeing Company [5] has estimated the cost of a heliostat field, tower, and receiver having a 230-MW net thermal output to be about \$40.5 million in mid 1976. In mid 1978, the cost would be

$$40.5 \left( \frac{217.9}{192.1} \right) = \$46 \text{ million}$$

This figure is probably low because the heliostat cost was taken to be \$60 per m<sup>2</sup>, a cost well below that presently obtainable.

## 2. Turbines

The installed cost of a General Electric 100 MW<sub>e</sub> high back-pressure turbine has been estimated to be between \$6 and 6.5 million dollars. This estimate is based upon the recent experience of G. E. in the construction of similar turbines. The cost quoted includes support equipment such as boiler feed pumps, control equipment, etc. For the base case, the turbine system consists of two turbines, each of about 16 MW<sub>e</sub> capacity. In the absence of definitive information about scaling turbine costs, we have taken turbine costs to vary as the 0.6 power of rated capacity. Such an approach gives a total turbine cost of \$4 million (2 turbines).

## 3. Distillation Column

The column has been sized with 16 ideal trays and a reflux ratio of 2.1. Limiting vapor flow rates were estimated to be 0.63 m/sec

using equations presented by Treybal [26]; the design was based on 85% of the limiting velocity. Application of the general rules for design of bubble cap tray columns presented in the same work resulted in the following column dimensions:

Distillation Column

Number of trays:	16 Theoretical, 23 actual
Tray spacing:	0.46 m
Downcomer area:	1.8 m <sup>2</sup>
Tray area:	13.1 m <sup>2</sup>
Tower diameter:	4.4 m
Tower height:	10.6 m
Shell thickness:	0.01 m

Fabricated cost (ss): \$0.46 million

Installed cost (including piping, instrumentation, etc): \$0.61 million

Cost estimates were made by the method of Pikulik and Diaz [19]. This tower cost does not include the reboiler or distillate condenser. These will be included with the other heat exchangers in the next section.

4. Heat Exchangers

Detailed calculations involving the estimation of individual heat transfer coefficients, mean temperature driving forces, and pressure drops were carried out in sizing each exchanger. Costs were estimated from Popper [37] according to a general cost equation of the following form.

$$\text{Cost} = \left( \frac{\text{Base}}{\text{Cost}} \right) \left[ \frac{\text{Material}}{\text{Factor}} + \frac{\text{Installation}}{\text{Factor}} \right] \left( \frac{\text{Pressure}}{\text{Factor}} \right) \left( \frac{\text{Cost}}{\text{Index}} \right)$$

The base cost pertains to equipment made from carbon steel and is determined from Popper's data according to the heat exchange area

needed. The exchanger material required in this process is stainless steel, for which the material factor is 4.5. The installation factor was taken to be 1.3. Table 7.3 summarizes the sizes and costs of all heat exchangers. These costs represent the cost of equipment in place including interunit piping, electrical connections, and control systems. More detailed information about the heat exchanger designs is available in Hill [14].

#### 5. Storage

The calculations giving the volumes of the  $\text{SO}_2/\text{SO}_3$  and the oxygen storage are described in Chapter IV. The  $\text{SO}_2$  and  $\text{SO}_3$  are stored as liquids jointly in a number of spherical tanks. The thickness of each tank is determined by the diameter of the tank and by the 10-atmosphere pressure differential across the tank wall. The storage vessel costs were based on the basic \$3.20-per-kg price for equipment fabricated from carbon steel plus about 140% for installation.

The total installation and material cost of 23 spherical (mild steel) vessels 4.94 m in diameter and 1.33 cm thick is \$0.86 million. The total volume of these vessels is  $1452 \text{ m}^3$ , which represents storage of  $2.4 \times 10^6$  kg of  $\text{SO}_3$ .

A precise cost estimate for the oxygen storage is difficult. Cavern storage cost estimates range from  $\$6.5/\text{m}^3$  to  $\$390/\text{m}^3$  [22]. These rates correspond to a storage price ranging from \$0.1 to \$5.8 million for a cavern volume of  $14,900 \text{ m}^3$ . The extremes in the price range correspond to extremes in the construction; the low price is for very large reservoirs constructed not too far underground. The high price is associated with small, deep caverns. A cavern cost of

Table 7.3. Heat Exchanger Sizes and Costs.

Unit	Heat Duty (MW <sub>t</sub> )	Heat-Transfer Area (m <sup>2</sup> )	Installed Cost (\$K)	
HE-1	110.8	2,642	1,753	
SO <sub>3</sub> Vaporizer	52.6	619	438	
Preheater	44.9	743	507	
Reboiler	45.2	1,131	812	
Make-Up Reboiler	11.3	285	250	
Dist. Condenser	57.0	1,633	813	
				Charge Mode
				<u>\$5,483 K</u>
CFW Heater	1.56	235	170	
Trimmer (Air Cooled)	6.5	767	740	
HE-2	10.8	4,284	2,142	
HE-3	24	425	340	
SO <sub>2</sub> Vaporizer	8.8	129	135	
LTS BFW Heater	1.8	159	145	
LTS Trimmer (Air Cooled)	8.4	825	453	
LTR HE1-A	10.1	356	241	
LTR HE1-B	7.1	206	176	
LTR HE-2	12.3	143	137	
LTR HE-3	8.4	130	132	
LTR HE-4	2.4	116	118	Discharge Mode
			<u>\$9,502K</u>	<u>\$4,019K</u>

\$200/m<sup>3</sup> will be used in these calculations because the cavern used for oxygen is at neither extreme. It is assumed that the excavated cavern will be lined with mild steel sheets (about 1/4-in. thick) supported by the rock wall and concrete poured between the wall and the lining. A rate of \$200/m<sup>3</sup> corresponds to a cavern cost of \$3.0 million. Further experience of the industry with the excavation of caverns for fluid storage may eventually yield better estimates.

#### 6. Reactors and Catalysts

The low-temperature reactors represent a relatively small investment when compared with other major process equipment. They have a total volume of 29.2 m<sup>3</sup> divided between five vanadium beds and three platinum beds. If the total pressure drop across all eight beds is limited to one atmosphere, pressure-drop calculations using the Ergun correlation [18] reveal that a minimum cross sectional area of 8.3 m<sup>2</sup> is required.

Typical sulfur dioxide oxidizing reactors have one or two shells with trays in them that support the catalyst. Partially reacted gas is withdrawn between stages, cooled in heat exchangers, and returned to the reactor. A possible configuration for the low-temperature reactors in this system utilizes two shells: one shell containing LTR 5 (a reactor volume of 18.2 m<sup>3</sup>), and the other shell containing all of the other reactor beds. For estimation of the cost of these reactors, the following assumptions were made: for shell 1 (LTR's 1 through 4), the shell thickness is 3.33 cm; the partitions between beds are steel sheets 1.0 cm thick; and spaces of 25 cm on each side of each partition are empty of catalyst and are needed for gas distribution. For shell 2, the shell thickness is 2.6 cm. Hence the total volume

in shell 1 is 23.7 m<sup>3</sup>, and the total volume in shell 2 is 18.2 m<sup>3</sup>. The cost of shell 1 is \$205,000, and the cost of shell 2 is \$117,000, based upon the weight of metal used. Installed cost is 2.4 times the fabricated cost and thus is \$772,000.

Vanadium pentoxide catalyst costs vary depending upon the quantity purchased, the manufacturer, support used, etc. The total mass of supported V<sub>2</sub>O<sub>5</sub> required for the low-temperature reactors is 15,400 kg. Vendor-supplied cost data indicate that this much catalyst would cost approximately \$38 K, not including installation.

Price data for platinum catalysts were more difficult to obtain than for the vanadium. For the purposes of this estimate, the catalyst cost was assumed to be the cost of the platinum metal plus 10% for catalyst processing.

The platinized asbestos catalyst, which has a platinum concentration of 7% by weight, contains a total of 11.32 kg (364.0 troy oz) of platinum. The market price of platinum is currently \$320 per troy ounce. The total cost of the platinum catalyst is calculated to be \$128K.

A credit for platinum recovery may be claimed for this catalyst. Ninety per cent of the platinum will be recovered. If the cost of platinum inflates at the same rate as other costs, this platinum will not decrease in value. The full value of the reclamation credit may be claimed; this credit is \$115 K. The net cost of the platinum catalyst is therefore \$13 K.

The cost of the high-temperature reactor tubes is assumed to be included in the \$42.3 M spent for the receiver and mirror field. This cost is also assumed to include the cost of the Fe<sub>2</sub>O<sub>3</sub> catalyst used,



and the cost of applying it to the inner surface of the collector/ reactor tubes. While the cost of this operation is difficult to estimate, it is felt that the added cost will have little effect on the cost of the receiver.

### 7. Reactants

The most economical form in which to ship the system reactants to the project site is as liquid SO<sub>3</sub>. Shipping the SO<sub>3</sub> eliminates the need of transporting large volumes of high-pressure oxygen. A very large mass of SO<sub>3</sub> is required: 2.4 x 10<sup>6</sup> kg of SO<sub>3</sub> is stored in one day.

Cost data for large quantities of liquid SO<sub>3</sub> were not readily available. The assumption was made that such a large volume of SO<sub>3</sub> could be obtained at about the same cost per kg as for SO<sub>2</sub>. This assumption is supported by the observation that, even if such large-scale manufacture of SO<sub>3</sub> does not currently occur, a conventional sulfuric acid plant could be made over with relatively minor changes into an SO<sub>3</sub> plant. Furthermore, if this form of energy storage is seen as economical, construction of a grassroots SO<sub>3</sub> plant to supply SO<sub>3</sub> for a number of solar power plants may be feasible.

Chemical Marketing Reporter for June 1978 reports that the average cost for liquid SO<sub>2</sub>, when purchased by the tank, is \$148/ton. This corresponds to a total reactant cost, assuming the same cost for SO<sub>3</sub>, of \$364 K.

### 8. Dry Cooling Tower

Design of the dry cooling tower is beyond the scope of this report. The cost of this piece of equipment was estimated very roughly for a

"Heller" dry cooling system using 40°F ITD. The updated costs come to \$30,600 per MW of heat load. This corresponds to a cost of \$747 K for a tower for the 31 MW<sub>e</sub> power plant (24.4 MW<sub>t</sub>) by itself, or \$2,690,000 for the tower for the combined power and storage systems (63.5 MW<sub>t</sub> for the trimmer and the condenser of the distillation tower, or approximately 87.9 MW<sub>t</sub> total).

D. Summary of Costs

1. Entire Power Plant-Storage System

Costs for all equipment by major category are summarized in Table 7.4. The cost of the storage process equipment is seen to be about 24% of the total plant cost. Heat exchangers are responsible for most of the storage equipment costs owing to the large areas required. The cost of the oxygen and sulfur-oxide storage vessels must be viewed with respect to the amount stored; in this base case, the oxygen and sulfur dioxide would supply about 8.3 hours of power at the 31 MW<sub>e</sub> nominal load.

2. Incremental Cost of Storage

It is of interest to estimate the amount by which the total plant cost is increased owing to the presence of the storage system. In making this estimate, it is necessary to account for the increased cost of heliostats, tower, receiver, and cooling tower system needed for the storage system heat requirements.

For purposes of this estimate, the incremental costs of heliostats, tower, and receiver are taken to be proportional to the thermal input. A stand-alone 31 MW<sub>e</sub> solar power plant operating at 40% efficiency (dry cooling conditions) would need 77.5 MW<sub>t</sub> input. Thus, by using

Table 7.4. Plant Cost Summary

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Heliostats, Tower, and Receiver		\$46.0 M
Turbine Generators		4.0
Dry Cooling Tower		<u>2.7</u>
		52.7
Chemical Storage System (244 MW <sub>e</sub> -hr)		
Heat Exchangers	\$9.5 M	
Distillation Column	0.6	
Low Temperature Reactors and Catalyst	0.8	
Reactants	0.4	
Storage Vessels		
O <sub>2</sub> (steel-lined caverns)	3.0	
SO <sub>x</sub> (mild steel tanks)	<u>0.9</u>	
Total Storage Equipment	\$15.2 M	\$15.2 M
TOTAL	Power plant with storage system	<u>\$67.9 M</u>

---

the \$46 million cost for a 230 MW<sub>t</sub> heliostat-tower-receiver system, the incremental cost of this equipment is

$$46 \left( 1 - \frac{77.5}{230} \right) = \$30.6 \text{ million}$$

The dry cooling system incremental cost is also taken in direct proportion to the cooling heat load. Calculations accounting for changes in steam cycle flows upon displacement of the storage system gave an incremental cost of \$1.8 million. There is an additional cost associated with the steam turbine because it has been split into 15 MW<sub>e</sub> and 16 MW<sub>e</sub> turbines, resulting in an increase of perhaps 20% in cost over a single 31 MW<sub>e</sub> turbine.

The incremental cost of storage is thus the sum of the following four items.

Storage system equipment	\$15.2 M
Heliostat-tower-receiver	30.6
Dry cooling system	1.8
Turbine split	<u>7</u>
Total Incremental Cost	\$48.3 million

### 3. Cost of Power

An estimate of the cost of electric power per kW-hr produced by the solar plant and the sulfur-oxide storage system may be obtained by deciding on a capitalization rate and an on-stream factor. The capitalization rate for the non-storage equipment is taken at 18%, 3% higher than the 15% used by Skinrod, et al. [35]. The higher rate acknowledges increased maintenance costs attributable to the presence of SO<sub>x</sub> and O<sub>2</sub> in the receiver tubes. An even higher rate

is taken for the storage equipment to account for maintenance costs due to corrosion. Peters and Timmerhaus [34] cite maintenance costs for high corrosion conditions of about 10%/year; we thus take the storage equipment capitalization rate to be 25% per year. The number of full capacity operating days is assumed to be 256 per year.

The cost of power is thus calculated to be

$$\begin{aligned} \text{cost} &= \frac{[46.0 + 4.0 + 2.7](0.18) + [15.2](0.25)}{256[8\{30.9 - 0.4 - 0.5 - 0.4\} + 16\{15.1 + 0.8 - 0.1 - 0.2 - 0.1\}]} \\ &= \$1.07 \times 10^{-4}/\text{W-hr} \\ &= 107 \text{ mils/kW hr} \end{aligned}$$

Similarly, the incremental cost of power produced from stored heat is

$$\begin{aligned} \text{cost} &= \frac{[48.3 - 15.2](0.18) + [15.2](0.25)}{256[16\{15.1 + 0.8 - 0.1 - 0.2 - 0.1\}]} \\ &= \$1.53 \times 10^{-4}/\text{W-hr} \\ &= 153 \text{ mils/kW-hr} \end{aligned}$$

## CHAPTER VIII. SENSITIVITY ANALYSIS

In the base case presented in Chapters II and III the energy and material balances for the chemical energy storage system were calculated for a specific set of operational parameters. This chapter discusses the response of the system to variations in the most important of these parameters. Their number is too great to permit investigating the effects of varying two or more of them simultaneously. However, the response of the system to the individual parameters may be used to try to select a more nearly optimum set than was chosen for the base case.

### A. Parameters Varied

The parameters selected for this study were:

- 1) The maximum tube-wall temperature in the solar reactor--the value of 880°C, chosen for the base case, may prove to be the highest practicable temperature, but it is instructive to be aware of the rewards and penalties associated with higher and lower values.
- 2) The temperature rise through the solar reactor--this is also the temperature difference,  $\Delta T_{5-6}$ , at the hot end of the heat interchanger, HE-1. Reducing  $\Delta T_{5-6}$  from the 140°C used in the base case not only increases the size needed for HE-1 but also influences the heat balance within the reactor.
- 3) The pressure in the solar reactor--pressures both above and below the 40 bar chosen for the base case were studied.
- 4) The temperature level of heat discharge to the environment,  $T_{min}$ --the value of 60°C used in the base case as the lowest temperature that could be reached by the system is a conservative estimate suitable for a hot desert location. Lower temperatures would be possible at many times of the year in most sites.

Two other process modifications were also studied--elimination of the distillation column for separating SO<sub>2</sub> and SO<sub>3</sub> during daytime operation and dissipating low-level heat to the environment instead of using it to heat boiler feedwater. The former step saves the energy input to the reboiler, but the SO<sub>2</sub> produced is diluted with a substantial quantity of SO<sub>3</sub>. The latter step results in some reduction in overall efficiency, but makes sizing of the power plant and the storage systems relatively independent of each other.

#### B. Restatement of Efficiency Indices

The three efficiencies defined in Chapter VII are used here as measures of the response of the system to variations of the parameters mentioned above. These efficiencies are:

##### Overall (2nd-law) Plant Efficiency

$$EOA = \frac{P_{DAY} \cdot \theta_{DAY} + P_{STO} \cdot \theta_{STO}}{(Q_{PR} + Q_{SR}) \theta_{DAY}}$$

##### Daytime Power Plant Efficiency

$$EPP = \frac{P_{DAY} \cdot \theta_{DAY}}{(Q_{PP} + Q_{BFW} - Q_{VAP} - Q_{REB}) \cdot \theta_{DAY}}$$

##### Thermal Storage Efficiency

$$ETS = \frac{\sum Q_{STO} \cdot \theta_{STO}}{(Q_{SR} + Q_{VAP} + Q_{REB} - Q_{BFW}) \cdot \theta_{DAY}}$$

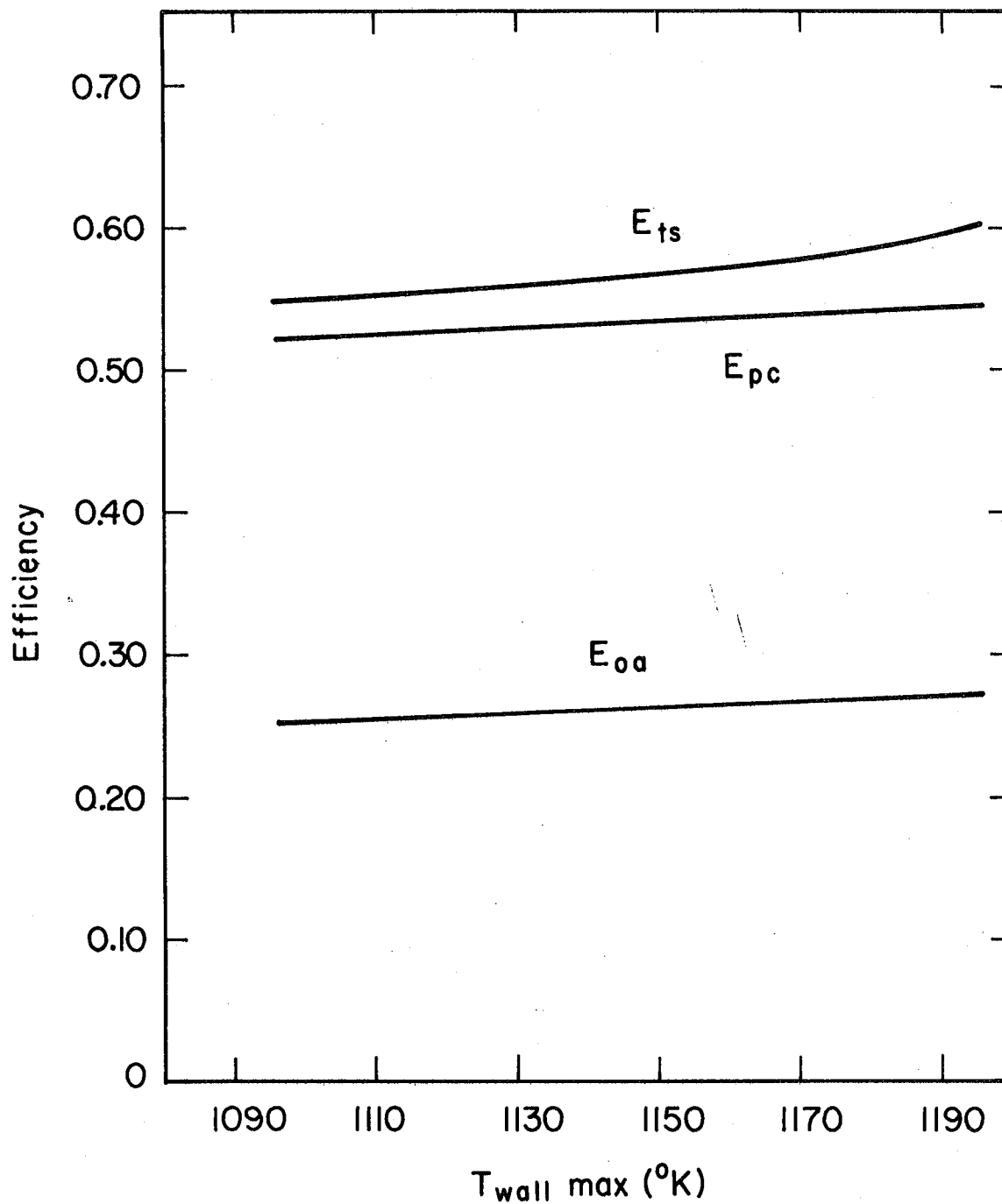
C. Effect of Tube-wall Temperature

Figure 8.1 shows the response of the system indices to variations in the maximum allowable tube-wall temperature. For reasons that are discussed below, the ratio  $Q_{pp}/Q_{SR}$  was set at 1.05 for this and the following parameter studies. The surprising result, shown in Fig. 8.1, is that  $E_{QA}$  is nearly independent of the value of  $T_{w \max}$ , increasing only about 1.5 percentage points for an increase of 100°. The slightly greater increase in  $E_{pp}$  is illusory. With the higher value of  $T_{w \max}$  there is a greater conversion of  $SO_3$  in the storage reactor. As a result, the quantity of  $SO_3$  fed decreases, since the total thermal input to the reactor is kept constant. A larger fraction of this thermal input is absorbed by the chemical reaction and a smaller fraction is converted to sensible heat of the reactor effluent. The reduced sensible heat flow means that more steam must be taken from the power plant for the vaporizer and reboiler, which increases the value of  $E_{pp}$ .  $E_{TS}$  increases with  $T_{w \max}$  because of the increased conversion of thermal input to chemical energy.

D. Effect of Temperature Rise in the Reactor,  $\Delta T_{5-6}$

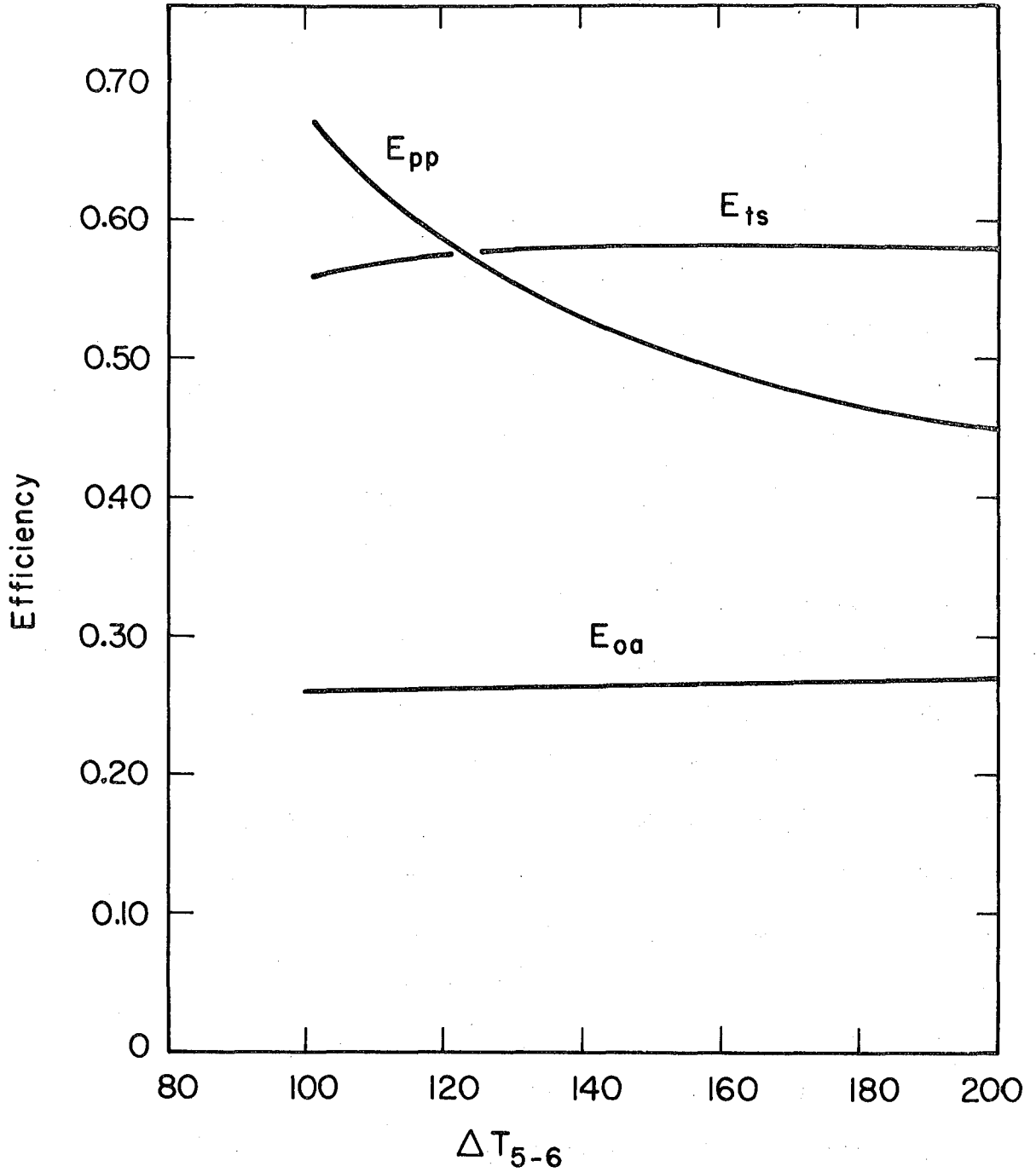
Figure 8.2 shows the response of the system to the temperature rise in the reactor, with  $T_{w \max}$  kept constant. Increasing  $\Delta T_{5-6}$  thus implies a decrease in the feed temperature at the inlet to the reactor and an increased  $\Delta T$  throughout the heat interchanger HE-1. The larger heat-transfer driving force reduces the area required for HE-1 correspondingly. Increasing  $\Delta T_{5-6}$  also means that a larger fraction of the heat absorbed by the gas stream is used to increase the sensible heat of the stream, and a smaller fraction is converted to chemical





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Fig. 8.1. Efficiencies vs. maximum reactor wall temperature.



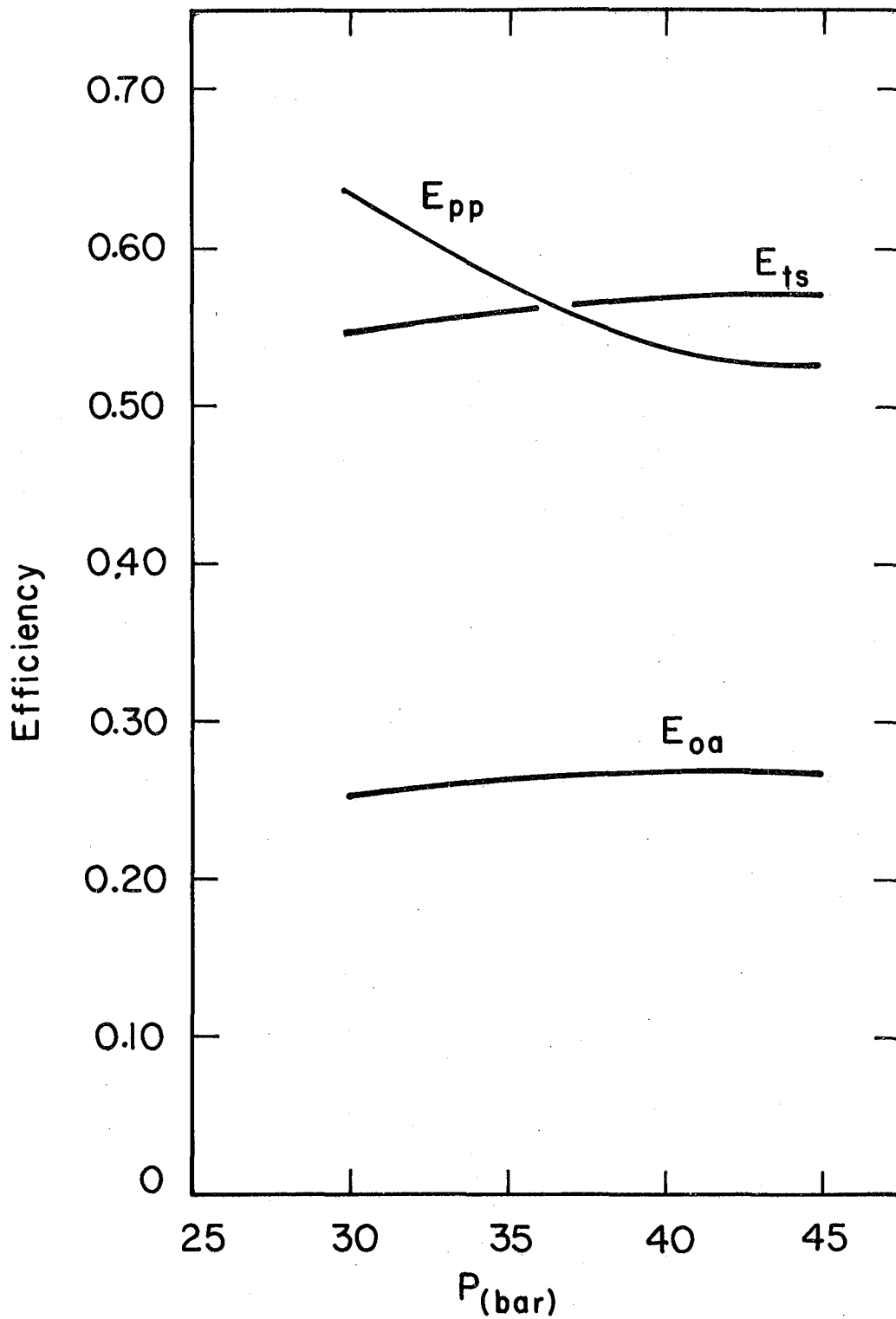
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Fig. 8.2. Efficiencies vs. temperature increase across reactor.

energy. As a result, the flow of  $\text{SO}_3$  per unit of heat absorbed in the reactor must increase. However, the fractional conversion of  $\text{SO}_3$  stays nearly constant. Because less heat is interchanged in HE-1 with increasing  $\Delta T_{5-6}$ , relatively more heat is available from the reactor effluent for the vaporizer and reboiler. In effect, the heat duty for those operations has been partially shifted from the power-plant receiver tubes to the storage-reactor receiver tubes. The value of  $E_{pp}$  drops because of this shift, but  $E_{QA}$  and  $E_{TS}$  are nearly unaffected. This means that  $\Delta T_{5-6}$  may be chosen so as to minimize the total costs of the heat exchangers without paying an appreciable penalty in overall efficiency.

E. Effect of Changing Pressure, P, in the Solar Receiver-Reactor

Figure 8.3 shows the effect of pressure on the system indices. Higher pressure reduces the fractional conversion of  $\text{SO}_3$  to  $\text{SO}_2$  and  $\text{O}_2$  because of the mass-action effect. However, this effect is overshadowed by the increase in temperature in the  $\text{SO}_3$  vaporizer and in the reboiler, and by the increased range of temperature in which condensation of  $\text{SO}_3$  and  $\text{SO}_2$  occurs as the reactor effluent is cooled. At low pressure the low temperature of condensation means that only a small fraction of the heat of condensation will be absorbed by the boiler feed water. However, at low P a larger fraction of the heat for the reboiler must be supplied by steam from the power plant. Thus,  $E_{pp}$  shows the gain that results from higher steam usage by the storage system. There are slight drops in  $E_{QA}$  and  $E_{TS}$  at the lowest pressure, but the effects are so small as to be of negligible importance. An effect that is not shown by these indices is that on the required volume for gas storage. Because the gas-storage vessels are considered



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Fig. 8.3. Efficiencies vs. pressure (HTS).

"empty" when the pressure of the stored gas has dropped to that of the discharge system, reducing the operating pressure of the charge will increase both the volume and the cost of those vessels.

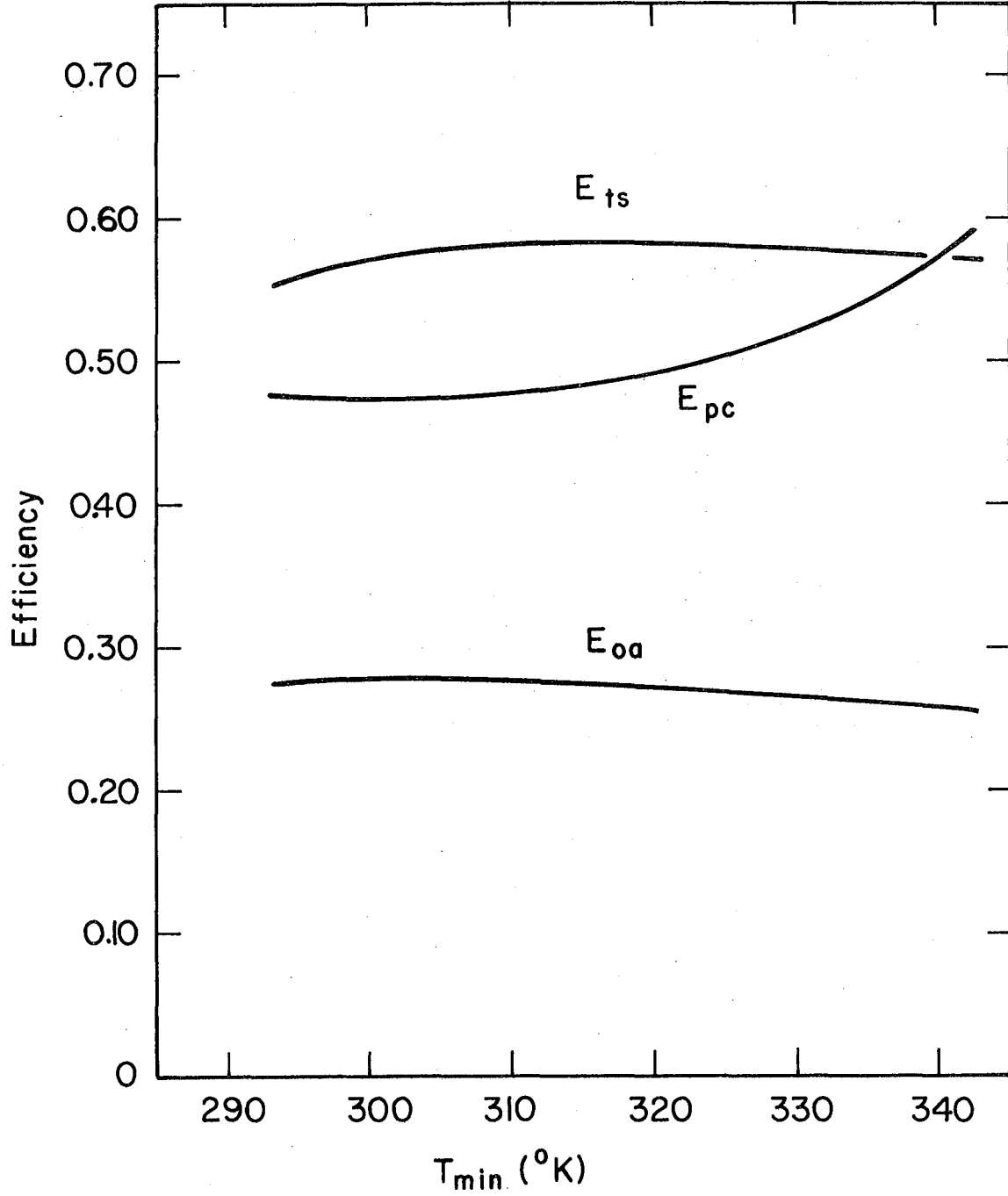
#### F. Effect of Minimum System Temperature, $T_{min}$

As was mentioned previously, the minimum system temperature for the base case, 60°C, was chosen to simulate the effect of using dry cooling in a desert environment. The minimum temperature at which heat can be transferred to the environment sets the pressure for the condensers for the steam turbines, the temperature of the boiler feed-water, the temperature and pressure in the condenser of the distillation column, and the temperature in the reboiler of the distillation column. It is clear from basic thermodynamic principles that reducing  $T_{min}$  will improve the efficiency of the power plant operations. Figure 8.4 shows this as well as other effects.

As  $T_{min}$  is reduced from the base case value, the temperature of the boiler feed water is reduced and a given flow of BFW absorbs a larger fraction of the heat of condensation of the  $SO_2$  and  $SO_3$  in the reactor effluent. The result is an improvement in the overall heat economy, as indicated by the rise in  $E_{QA}$ .  $E_{pp}$  is reduced at lower values of  $T_{min}$ , but this again is the reflection of the fact that receiving BFW preheat reduces the efficiency index for the power plant. The slight maximum in the value of  $E_{TS}$  has a similar effect, and one can say that that index is effectively independent of  $T_{min}$ .

#### G. Effect of Eliminating the Distillation Column

The reboiler of the distillation column requires a substantial heat input in the form of intermediate-pressure steam from the power



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Fig. 8.4. Efficiencies vs. minimum system temperature.

plant. Elimination of the distillation column would eliminate that heat load and would also eliminate the cost of the column. On the other hand, elimination of the column would require storage of most of the  $\text{SO}_2$  in the form of a solution in  $\text{SO}_3$ , roughly tripling the liquid storage volume required for a given quantity of energy storage. In addition, the sizes of the flow lines, heat exchangers, and reactors would have to be increased to accommodate the flow of the inert component, and the amount of low level heat dissipated to the environment in the nighttime trimmer would be increased. These effects are compared by considering the effect of eliminating the distillation column while keeping other system parameters the same as in the base case. The results are shown in Tables 8.1, 8.2, and 8.3.

Table 8.1 shows the changes in the system indices, power, and reactor feed rates that result from eliminating the distillation column. There is a small gain in overall efficiency and an increase in  $P_{\text{Day}}$  at the expense of  $P_{\text{Sto}}$ . The increase in feed rate to the high-temperature reactor is small, but the increased feed to the LT reactor is substantial and would be mirrored by the increased requirement for liquid storage and the sizes of the LT heat exchangers.

The reasons why the change in  $E_{\text{OA}}$  is so small even though  $E_{\text{pp}}$  and  $E_{\text{TS}}$  change substantially are found from an examination of the energy balances shown in Tables 8.2 and 8.3. These can be compared to those in Tables 7.1 and 7.2 for the base case. For the base case (with distillation) intermediate-pressure steam supplies  $511.3 \text{ MW}_t \cdot \text{hr}$  to the  $\text{SO}_3$  vaporizer and make-up reboiler. This is reduced to  $249.2 \text{ MW-hr}$  by eliminating the distillation column, and the net power plant

Table 8.1. Effect of eliminating distillation column and BFW preheat.

	Base Case		
	w Dist.	w/o Dist.	w/o BFW Preheat
<u>Efficiencies</u>			
EOA	0.263	0.276	0.257
EPP	0.534	0.408	0.542
ETS	0.579	0.818	0.574
<u>Power and Flow Rates</u>			
P <sub>Day</sub> (MW <sub>e</sub> )	30.9	39.4	
P <sub>Sto</sub> (MW <sub>e</sub> )	15.1	12.2	
LT react. feed rate (Stream 27) (kmol/s)	2.69	2.78	
HT react. feed rate (Stream 5) (kmol/s)	0.76	1.65	



Table 8.2 Total Plant Energy Balance. Base Case Without Distillation.

	<u>MW (e or t)</u>	<u>MW-hr (e or t)</u>
<b>I. <u>Inputs</u> (8 Hours Daytime)</b>		
Power Plant Receiver	117.8 (t)	1840 (t)
Storage Receiver	<u>112.2</u>	
Total Inputs	230.0 (t)	<u>1840 (t)</u>
<b>II. <u>Outputs</u></b>		
<b>A. Daytime (8 Hours)</b>		
Generator Terminals	39.4 (e)	
Parasitic Power		
BFW Pump	(0.4)	
SO <sub>3</sub> Pump	(0.5)	
Cooling System Power	<u>(0.4)</u>	
Net Power	38.1 (e)	<u>304.8 (e)</u>
Waste Heat		
Trimmer	22.2 (t)	
Turbine Steam Leaks	0.4	
LP Turbine Condenser	53.1	
Misc. Heat Losses	<u>3.4</u>	
Total Waste Heat	79.1 (t)	<u>632.9 (t)</u>
<b>B. Nighttime (16 Hours)</b>		
Generator Terminals	12.4 (e)	
Gas Turbine	.8	
Parasitic Power		
BFW Pump	(.1)	
SO <sub>2</sub> Pump	(.6)	
Cooling System Power	<u>(.2)</u>	
Net Power	12.3 (e)	196.8 (e)
Waste Heat		
Trimmer	19.3 (t)	
Small Turbine Condenser	20.3	
Large Turbine Bleed	2.9	
Misc. Heat Losses	<u>1.6</u>	
Total Waste Heat	44.1 (t)	705.5 (t)
Total Outputs		<u>1840</u>

Table 8.3 Storage System Energy Balance. Base Case Without Distillation.

---

	<u>MW-hr</u>
<b>Inputs</b>	
Daytime	
Solar Receiver	897.6 (t)
SO <sub>3</sub> Vaporizer	249.2 (t)
Liquid SO <sub>3</sub> Pump	4.0 (e)
Total Inputs	<u>1152.4</u>
<b>Outputs</b>	
Daytime	
Boiler Feed Preheat	46.9 (t)
Trimmer	177.9 (t)
Misc.	7.4 (t)
Daytime Total	<u>232.2</u>
Nighttime	
Boiler Feed Preheat	39.4 (t)
Trimmer	308.2 (t)
LTR Reactors (QAAN)	551.4 (t)
Gas Turbine Work (isentropic expansion)	13.9 (e)
Misc.	7.4 (t)
Nighttime Total	<u>920.2</u>
Total Outputs	1152.4

---

output increases from 29.6 MW<sub>e</sub> to 38.1 MW<sub>e</sub> as a result. However, in the latter case the load to the daytime trimmer increases from 52.1 MW<sub>t</sub>-hr to 177.9, and the dissipation in the nighttime trimmer increases from 133.7 to 308.2 MW<sub>t</sub>-hr. The added daytime trimmer load results from shifting the heat of condensation of the SO<sub>2</sub> - SO<sub>3</sub> mixture from the reboiler. The added nighttime trimmer load is the result of the large increase in SO<sub>3</sub> flow around the nighttime system.

It appears likely that the optimum process configuration would feature a distillation column without a make-up reboiler. This would utilize the heat of condensation of the SO<sub>2</sub> - SO<sub>3</sub> mixture, which is otherwise wasted, to concentrate the SO<sub>2</sub> significantly, but not to the 99% purity that was specified for the base case. Nighttime efficiency, liquid storage volume, and heat exchanger areas would thereby be improved without diverting steam from the daytime power plant. An improvement of 0.01 in E<sub>OA</sub> might thereby be achieved, together with an increase of nighttime power output of between 1 and 2 MW<sub>e</sub>.

It appears unlikely that changing the process flowsheet to the configuration of limited distillation would have a significant effect on the response of the system to the changes in process parameters discussed above.

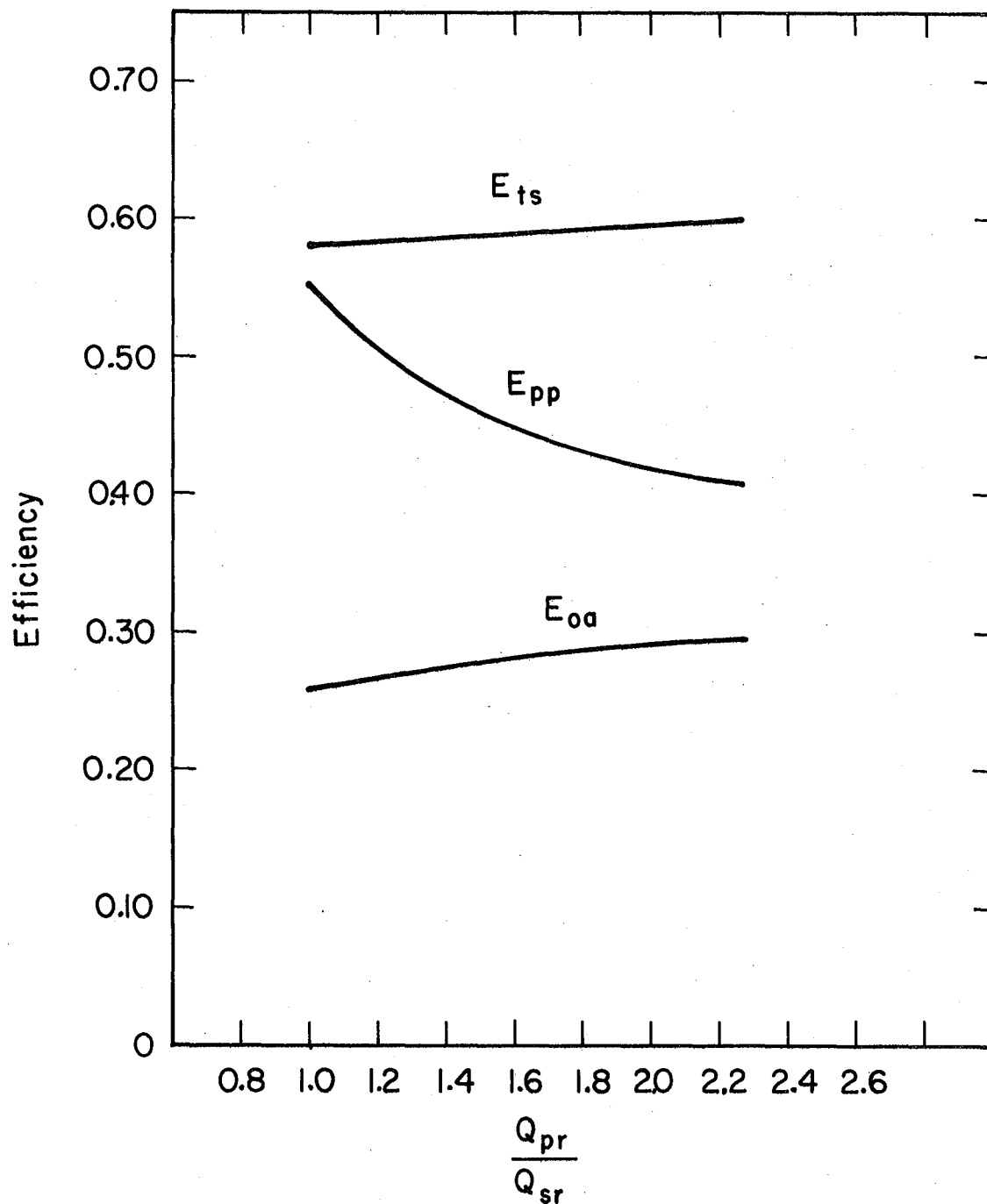
#### H. Effect of Eliminating Boiler Feed Water Preheat

In the base case low-level heat is utilized to the extent considered practicable to preheat boiler feed water for the daytime power plant. This energy saving maximizes E<sub>OA</sub>, but it is of interest to determine just how important the saving is in order to gain perspective. To this end the result of eliminating all BFW preheat

during the day from the system operating under base-case conditions was determined. The impact on the efficiency indices is also shown in Table 8.1. The effect is small--a slight decrease in  $E_{QA}$  and  $E_{TS}$ , and a slight increase in  $E_{pp}$ . The effects are so small because the temperature level of the heat being discarded is so low. It is thus clear that the value of this low-level heat should not be over-emphasized in conceptualizing modifications for the design of this type of storage system.

#### I. Effect of Varying $Q_{PR}/Q_{SR}$ on System Performance

Because of the heat interchange between the daytime power plant and the storage system, there is an optimum ratio of thermal inputs to the two that minimizes dissipation of heat to the environment. However, this ratio is not necessarily the most desirable from the standpoint of nighttime generating capacity relative to daytime capacity. It is therefore of interest to determine the effect of varying the ratio  $Q_{PR}/Q_{SR}$  on the efficiency indices. This variation is shown in Fig. 8.5 for values of the ratio between 1.0 and 2.25. The overall system efficiency increases as the value of the ratio increases. However, as was shown in the previous section, this increase is not due primarily to the more optimal use of low-level heat. Rather, it is the result of the fact that the daytime power plant is inherently more efficient at producing power than is the storage system. (If there were no storage system associated with it, the steam cycle used for the power plant would have an efficiency of about 0.40). Thus, if the ratio of  $Q_{PR}/Q_{SR}$  is increased the primary increase in  $E_{QA}$  is simply due to weighted averaging. The drop in  $E_{pp}$  as the ratio increases is



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Fig. 8.5. Efficiencies vs.  $\frac{Q_{pr}}{Q_{sr}}$  (steam) (storage).

primarily the result of having a smaller fraction of the total steam produced being sent to the storage system, and is thus an artifact of the method of energy accounting. The increase in  $ETS$  is real, since the storage system is being credited with the increased usage of low-level heat that the larger ratio makes possible. However, the conclusion that one draws from this study is that the ratio of thermal inputs to the two systems should be set by the desired ratio of  $P_{Day}/P_{Sto}$ , since there is a negligible penalty associated with varying the relative sizes of the two systems within the ranges studied.

#### J. Duration of Storage

The base case presented in Chapters II and III is sized to provide 16 hours of storage-generated power at a rate about half that of the daytime power plant. As was noted above, the design of the storage system could readily be modified to allow discharge at a more rapid rate. However, there appears to be a significant advantage to keeping the high-pressure steam turbines hot at all times to avoid the delay of cold start-up. Any modification of the proposed design should probably make provision for generating sufficient high-pressure steam at all times to keep those turbines on hot stand-by when they are not being used for power generation.

Modification of the system to allow for more than 16 hours of operation from storage also appears to be straight-forward. There is only a slight sensitivity of the system to variations in  $Q_{PR}/Q_{SR}$ . It thus appears that there would be little efficiency penalty in making  $Q_{SR}$  large enough to allow some accumulation of stored  $SO_2$  and  $O_2$  above nighttime usage for periods of a week or longer. The cost of the

storage tanks themselves would be the primary additional cost involved in providing the capability of generating power from the storage system for periods of several days at a time.

It would appear unlikely, on the other hand, to be economical to provide overnight storage for a solar power plant by a second type of energy-storage system while having a chemical system for longer-term storage. The high capital investment required to install a chemical-energy storage system would make it desirable to use it for all of the energy-storage requirements of the installation. Although a sensible-heat or latent-heat storage system might prove advantageous as buffer (less than 1-hour) storage for the daytime power plant, longer-term storage should be provided by a single energy storage system.

#### K. Accuracy of Calculational Methods

The calculations presented in this report are based on a number of assumptions regarding physical properties, reaction kinetics, and heat and mass transfer behavior. In some cases the error in these assumptions can be estimated with reasonable accuracy whereas in others experimental data are needed to improve the certainty. In the following discussion a number of these assumptions will be examined.

##### 1. Physical Properties

The three system components,  $O_2$ ,  $SO_2$  and  $SO_3$ , were assumed to follow ideal gas behavior in the vapor phase. This assumption is quite accurate except at temperatures near the dew point. The uncertainty introduced is that the predicted pressure drops will be somewhat high, and thus conservative.

Ideal heat capacities were assumed, with no allowance being made for the effect of pressure. This assumption for  $\text{SO}_3$  gives a value that is about 40% too low at the boiling point at 40 bar. The error becomes negligible after the temperature of the  $\text{SO}_3$  vapor has risen about  $200^\circ$ . The effect of the error is to underestimate by a few percent the duty of heat exchanger HE-1. The error is less than the uncertainty in the heat-transfer coefficients.

The distillation column design is based on the assumption that  $\text{SO}_2$  and  $\text{SO}_3$  form ideal solutions. This assumption is based on general chemical principles and should be tested experimentally if it seems economically desirable to have a distillation column. If there is significant interaction between the two molecules then the number of theoretical stages required may be greater than the number calculated. However, it seems likely that the uncertainty in the predicted tray efficiency is greater than that in the equilibrium behavior.

## 2. Transport Properties

Heat- and mass-transfer coefficients were estimated from the standard correlations. The accuracy of such correlations is typically  $\pm 50\%$ . Since the projected cost of the heat exchangers is a major fraction of the cost of the storage system, more accurate cost data for the storage system should be obtained before it is developed further. The very large sizes of the gas-gas heat exchangers makes an accurate estimation of their cost particularly difficult.

The behavior of the storage solar receiver-reactor is based on the assumption that the reactor tubes can be coated on the inside surface with a suitably reactive catalyst. If the reactivity of the



catalyst is sufficiently high, then heat transfer and mass transfer will control the reaction rate rather than reaction kinetics. The small amount of experimental kinetic data obtained in this work makes this assumption plausible.

It was also assumed that the reactor tubes were heated by a single, uniform radiative source. The reactor design has a maximum permissible wall temperature as one constraint. It would thus be necessary to model the radiative flux in an actual receiver more accurately than was done here to be sure that the temperature limitation was not exceeded.

The calculations indicate that there will be a substantial influence of mass-transfer resistance on the conversion of  $\text{SO}_3$  that occurs in the reactor tubes. Since the correlation used here is based on smooth-walled, straight tubes, one would want to obtain experimental data for a catalyst-coated tube of the desired geometry to validate the computational model.

### 3. Cost Data

The cost data used to estimate the capital requirements and operating expenses were obtained from the references cited in Chapter VII. It should be recognized, however, that much of the equipment proposed for this system is larger and/or made of material that is more exotic than is typical of plant in the chemical industry. In some cases experimental work will be required just to demonstrate that the proposed design is technically feasible. For these reasons the cost estimates have an accuracy that can be no more than +50%.

## CHAPTER IX. CONCLUSIONS AND RECOMMENDATIONS

The sensitivity analysis has shown the chemical-energy storage system to be remarkably insensitive to the parameters that were chosen for study. Additional parameters that might have more effect do not come readily to mind. It thus appears that the following conclusions can be drawn:

- 1) There is no particular incentive to increasing the allowable tube-wall temperature much above 800°C, although operation at 850°C would be slightly advantageous.
- 2) Heat interchange between the solar reactor feed and the reactor effluent does not have a significant effect on the system efficiency. The entire heat-exchange operation (interchanger, vaporizer, reboiler, BFW preheater, and trimmer) should thus be designed to minimize costs.
- 3) The pressure of operation does not have a large effect on system efficiency, but should be of the order of 40 bar to minimize costs of gas-storage vessels.
- 4) The ratio of solar thermal inputs to the daytime power plant and the storage reactor should be set to give the desired ratio of daytime power and power from storage.
- 5) The reflux ratio and the number of plates in the distillation column should be adjusted to eliminate the need for the make-up reboiler and to minimize the steam requirement in the SO<sub>3</sub> vaporizer.
- 6) A chemical energy storage system should be designed to provide all of the energy storage required for a solar power plant, not just the long-term storage.

The cost analysis of the process configuration developed in this study shows that the heat exchangers represent a major fraction of the total cost of the storage system. Furthermore, the heat-exchange networks used during charging of the storage system and during discharge are independent and somewhat redundant. Further development of this process should aim at reducing the cost of the system through reducing the size and/or number of heat exchangers employed. A possible method of accomplishing this would be to eliminate the heat interchanger HE-1 and to use the hot reactor effluent to generate steam during the day in the same set of boilers that is used in generating power from storage. Such a process configuration would have the added advantage of avoiding the costly piping necessary to carry high-pressure water and steam to the top of the solar receiver and back. In addition, modification of the process in this manner would facilitate switching the system from charge mode to discharge mode, making its use for short-term storage practical.

Finally, it must be emphasized that the components of the system studied here,  $\text{SO}_3$ ,  $\text{SO}_2$ , and  $\text{O}_2$ , pose severe problems of corrosion and toxicity under many of the process conditions that have been proposed. These problems may or may not have solutions that are technically and economically feasible. In the light of these and other matters discussed in this report this chemical process would have to offer a clear advantage over alternative methods of energy storage before further development were undertaken.

REFERENCES

1. Alloy Digest Co62 Jan 1971.
2. Alloy Digest SS137 Oct 1962.
3. Angerman, C. L., Oxidation of Metals, 5, 149 (1972).
4. Bhakta, M., "Chemical Storage of Thermal Energy Using the  $\text{SO}_3\text{-SO}_2\text{-O}_2$  System," U. C. Berkeley MS Thesis, 1976.
5. Boeing Engineering and Construction, "Closed Cycle, High-Temperature Central Receiver Concept for Solar Electric Power," EPRI EM-256, Dec. 1976.
6. Chattophyay, B., and G. C. Wood, J. Electrochem. Soc., 117, 1170 (1970).
7. Clay, D., "Development of a Feasible Process for the Simultaneous Removal of Nitrogen Oxides and Sulfur Oxides from Fossil Fuel Burning Power Plants," U.C. Berkeley Ph.D. Thesis, 1974.
8. CRC Handbook of Chemistry and Physics, 51st Ed., 1970 Chemical Rubber Company, Cleveland.
9. Davidson, M. and D. Grether, "The Central Receiver Power Plant: An Environmental, Ecological, and Socio-economic Analysis," LBL Report 6329, 1977.
10. Dayan, J., A. S. Foss, and S. Lynn, "Evaluation of a Chemical Heat Storage System for a Solar Steam Power Plant." 12th Intersoc. Energy Conv. Engr. Conf. pg 1181, Washington, D.C. Aug. 1977.
11. Eklund, R. B., "The Rate of Oxidation of Sulfur Dioxide with a Commercial Vanadium Catalyst," Almquist and Wiksell, Stockholm 1956.

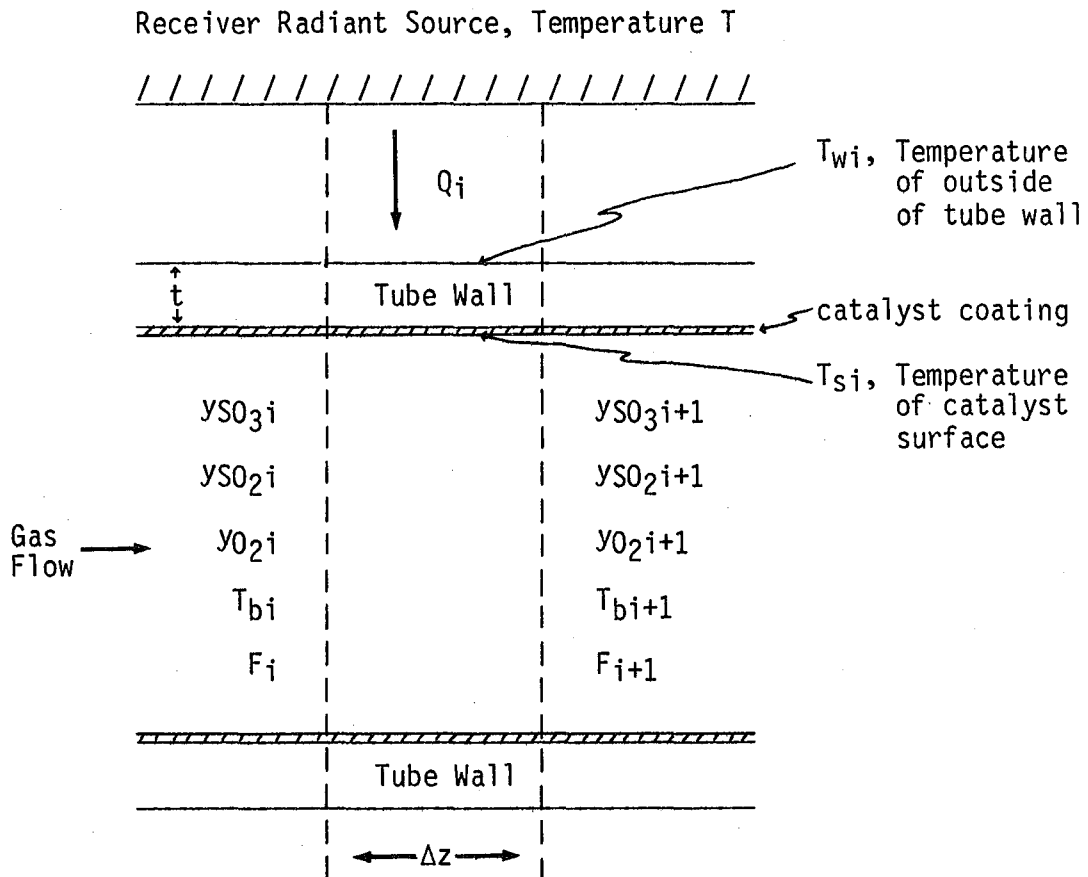
12. Fairlie, A. M., "Sulfuric Acid Manufacture," Reinhold Publishing Corporation, New York 1936.
13. Herce, J. L., J. B. Gros, and R. Bugarel, Chem. Eng. Sci., 32, 729 (1977).
14. Hill, S. A., M. S. Thesis, Univ. of Calif., Dept. of Chem. Engr. (1978).
15. Lewis, W. K. and E. P. Ries, Ind. Eng. Chem., 19, 83 (1972).
16. Livbjerg, H. and J. Villadsen, Chem. Eng. Sci., 27, 21 (1972).
17. Lord, R. C., P. E. Minton, and R. P. Slusser, Chem. Eng., Jan 26, pg. 96 (1970).
18. Mars, P. and J. G. H. Maessen, J. Catal., 10, 1 (1968).
19. Perry, ed. Chemical Engineer's Handbook, 5th Ed., McGraw-Hill Book Company, New York 1973.
20. Pikulik, A. and Diaz, H. E., Chem. Eng., Oct 10, p. 106 (1977).
21. Rahmel, A., Oxidation of Metals, 9, 401 (1975).
22. Richards, C. W., "Engineering Material Science," Wadsworth Publishing Co., Inc., San Francisco, 1961.
23. Ridgeway, S. L. and J. L. Dooley, "Underground Storage of Off-Peak Power," Proceedings 11th Intersociety Energy Conversion Engineering Conference, Nevada, 1976.
24. Rohsenow, W. M. and J. P. Hartnett (Ed.), Handbook of Heat Transfer, McGraw-Hill Book Company, New York, 1973.
25. Spewock, S., Brecher, L. E., and J. F. Pierre, "An Evaluation of Catalysts for the Thermal-Catalytic Reduction of Sulfur Trioxide," Westinghouse R&D Center, Pittsburgh, 1977.

26. Tong, L. S., "Boiling Heat Transfer and Two-Phase Flow," Robert E. Krieger Publishing Company, Huntington, 1975.
27. Treybal, R. E., "Mass Transfer Operations," McGraw-Hill Book Company, New York, 1968.
28. Uyehara, O. A., and Watson, K. M., Ind. Eng. Chem., 35, 541 (1943).
29. Vasantasree, V. and M. G. Hooking, Corrosion Science, 16, 261 (1976).
30. Whittle, D. P. and G. C. Wood, J. Electrochem. Soc., 115, 126 (1968).
31. Larinoff, M. W., "Dry Cooling Tower Power Plant Design Specifications and Performance Characteristics," ASME Paper, Detroit, Michigan, November 1974.
32. Nickless, G., "Inorganic Sulphur Chemistry," Elsevier Publishing Company, Amsterdam, 1968.
33. General Electric Turbine Design Drawing 414 HB 725.
34. Peters, M., Timmerhaus, K., Plant Design and Economics for Chemical Engineers, McGraw Hill, 1965.
35. Skinrood, A.C. et al., Sandia Laboratory, Report SAND 74-8017, Sept., 1974.

APPENDIX A. EQUATIONS FOR THE HIGH-TEMPERATURE REACTOR MODEL

Notation

Equations are written for an incremental reactor length. The diagram below displays some of the notation.



Other Notation:

$y_{SO_3}^0, y_{SO_2}^0, y_{O_2}^0$  - mole fractions in feed gas

$F_0$  - molar flow rate of feed per tube

$P$  - pressure

$d_o, d_i$  - outside and inside tube diameter

$L$  - number of increments

Assumptions

1. Chemical reaction reaches equilibrium on catalyst surface.  
Rate of chemical conversion is limited by the rate of diffusion of SO<sub>2</sub> from catalyst surface to bulk gas.
2. Gas is in plug flow; there are no radial gradients outside of boundary layer.
3. Uniform source temperature throughout receiver.
4. Heat capacity of gas mixture on mass basis is independent of gas concentration.
5. Ideal gas laws apply.

Equations

Radiant heat flux from receiver source

$$Q_i = \sigma(T^4 - T_{wi}^4) \quad (1)$$

Heat flux balance at exterior surface of tube wall

$$Q_i = \frac{k_w}{t} (T_{wi} - T_{si}) \quad (2)$$

Heat flux balance at catalyst surface

$$Q_i = h(T_{si} - T_{bi}) + (\Delta H_R)kgP \left[ (y_{SO_2})_s - y_{SO_2} \right]_i \quad (3)$$

Chemical equilibrium at the surface

$$K_p(T_s) = \frac{(p_{SO_2})_s (p_{O_2})_s^{1/2}}{(p_{SO_3})_s}$$

By stoichiometry,

$$K_p(T_s) = \frac{(y_{SO_2}^0 + y_{SO_3}^0 x)}{y_{SO_3}^0 (1-x)} \left[ \frac{P(y_{SO_3}^0 x + 2y_{O_2}^0)}{2 + y_{SO_3}^0 x} \right]^{1/2}$$



$$K_p = 10^{(4.765 - 5022/T_s)} \quad (4a)$$

where

$x \equiv$  fraction of  $SO_3$  in feed stream that is converted at conditions of catalyst surface.

and

$$\left(y_{SO_2}^0\right)_s = \frac{y_{SO_2}^0 + y_{SO_3}^0 x}{y_{SO_3}^0 (1+x/2)} \quad (5)$$

Heat balance on gas

$$(F_o C_{po}) [T_{bi+1} - T_{bi}] = h(\pi d_i \Delta z) [T_{si} - T_{bi}] \quad (6)$$

Material balance on  $SO_3$  in gas

$$F_i y_{SO_3 i} - N_{ia} = \underbrace{\left(F_i + \frac{N_{ia}}{2}\right)}_{F_{i+1}} y_{SO_3 i+1} \quad (7a)$$

where

$$N_{ia} = kgP(\pi d_i \Delta z) \left[ \left(y_{SO_2}\right)_s - y_{SO_2} \right]_i$$

Material balance on  $SO_2$  in gas

$$F_i y_{SO_2 i} + N_{ia} = F_{i+1} y_{SO_2 i+1} \quad (7b)$$

Oxygen concentration by difference

$$y_{O_2 i+1} = 1 - \left[ y_{SO_3} + y_{SO_2} \right]_{i+1} \quad (7c)$$

Molar flow rate (from addition of Eqs. (7a) and (7b))

$$F_{i+1} = F_i \left[ \frac{y_{SO_3 i} + 2}{y_{SO_3 i+1} + 2} \right] \quad (8)$$

Total heat flux per tube

$$Q = (\pi d_o L \Delta z) \sum_{i=1}^L Q_i \quad (9)$$

Solution Sequence

The method of iterative solution is as follows:

1. Radiant source temperature  $T$  assumed (uniform for all increments).
2. For each increment, Equations (1) - (5) are solved iteratively for  $Q_i$ ,  $T_{wi}$ ,  $T_{si}$ ,  $x$ , and  $(y_{SO_2})_{si}$  by adjusting trial values of  $T_{wi}$  until satisfaction of the heat balances is achieved.  $\Delta z$  was taken = 0.2m.
3. Equations (6) - (8) yield  $T_{bi+1}$ ,  $F_{i+1}$ , and mole fractions at the (i+1)st increment.
4. When all increments have been calculated, the total heat flux per tube calculated by Eq. (9) is compared with the specified flux and adjustment made in the source temperature  $T$  if mismatch exists. Iteration from Step (1) is made until convergence is achieved.

Parameter values used in the calculations are given in Table A.1.

Table A.1. Parameter values for the High-Temperature Reactor Model.

<u>Parameter</u>	<u>Value</u> (or representative average value)	<u>Relationship</u>	<u>Reference</u>
$k_w$ tube thermal conductivity	35 J/s·m·K	-----	[18, Table 23.5]
$k_g$ convective mass transfer coefficient	$(1.14 \times 10^{-6} \text{ mol/s} \cdot \text{m}^2 \cdot \text{N} \cdot \text{m}^{-2})$	$Sh = 0.023Re^{0.81}Sc^{0.33}$	Nusselt correlation
$h$ convective heat transfer coefficient	$(350 \text{ J/s} \cdot \text{m}^2 \cdot \text{K})$	$Nu = 0.023Re^{0.81}Pr^{0.33}$	Nusselt correlation
$C_{p0}$ Gas molar heat capacity	$(75 \text{ J/mol} \cdot \text{K})$		[11]
$\Delta H_R$ Heat of reaction	$(86.6 \text{ kJ/mol})$	$98.3 - 1.09 \times 10^{-2}T + 7.07 \times 10^{-6}T^2 + \frac{628}{T-577}$	[11]
$\sigma$ Radiant heat flux constant	$5.67 \times 10^{-8} \text{ J/m}^2 \cdot \text{s} \cdot \text{K}^4$		
$SO_2$ diffusivity	$0.018 \text{ cm}^2/\text{s}$		[18, Eq. 3-29]
Gas viscosity	$4 \times 10^{-5} \text{ kg/m} \cdot \text{s}$		[18, Eq. 3-129]
Gas thermal conductivity	$0.043 \text{ J/s} \cdot \text{m} \cdot \text{K}$		[18, Eq. 3-102]
Critical constants	$SO_3$ $SO_2$ $O_2$		
$T_c$ $^{\circ}\text{C}$	218.3      157.2      -118.8		
$P_c$ atm	83.6      77.7      49.7		
$\rho_c$ g/cm <sup>3</sup>	0.63      0.52      0.43		

\*Actual calculations in HTR-routine uses MKhr units (m, kg, hr, Cal, C<sup>o</sup>, atm) rather than SI units as given in this table.

APPENDIX B. LOW-TEMPERATURE REACTOR COMPUTER MODEL

The temperature and concentration profiles in the low temperature reactor are calculated from incremental heat and material balances.

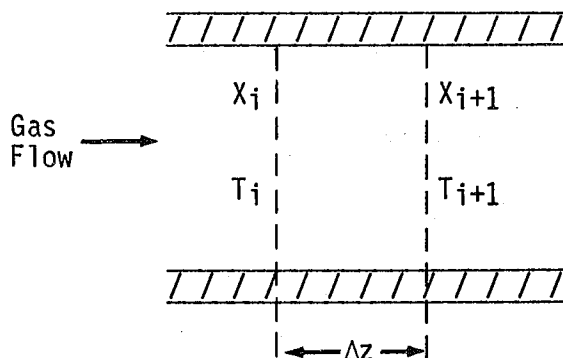


Fig. B-1. Diagram of spatial increment in LTR.

$X$  = bulk conversion

$T$  = bulk temperature

$\Delta z$  = length increment

Heat Balance:

$$(\Delta H_r)(X_{i+1} - X_i) = C_p(T_{i+1} - T_i) \quad (B-1)$$

Material Balance:

$$X_{i+1} - X_i = 1/F \quad r \cdot \rho_c \quad A \cdot \Delta z \quad (B-2)$$

Reaction rates over both  $V_2O_5$  and platinum catalysts are reported in the literature as overall rates (g-moles converted per sec per kg catalyst). Diffusion resistance and thermal resistance were therefore assumed to be incorporated into these effective reaction rates.

The kinetic expressions used are:

V<sub>2</sub>O<sub>5</sub> Catalyst (Mars + Maessen [17])

$$r = A e^{-E/RT} \frac{K P_{SO_2}/P_{SO_3}}{[1 + (K P_{SO_2}/P_{SO_3})^{1/2}]^2} \quad (B-3)$$

$$K = 2.3 \times 10^{-8} \exp(27200/RT); R = 1.98 \text{ cal/mole}^{\circ}K \quad (B-4)$$

	<u>Temperature Range, °C</u>	
	<u>420-454</u>	<u>454-600</u>
E, cal/mole	70,000	36,000
A	$1.56 \times 10^{17}$	$9.38 \times 10^6$

Herce et al. [13] give evidence that this relation is valid at pressures up to 10 atmospheres.

Platinum Catalyst (Lewis and Ries [14], Uyehara and Watson [20]).

$$r = \frac{k T e^{(-E/RT)}}{(1 + K_{O_2} P_{O_2} + K_{SO_3} P_{SO_3})^2} \left[ P_{SO_2} P_{O_2}^{1/2} - \frac{P_{SO_2}}{K} \right]$$

$$\ln K_{SO_3} = 21400/RT - 23/R$$

$$\ln K_{SO_2} = 20360/RT - 23/R$$

$$\ln K = 22980/RT - 19.5/R$$

$$E = 3690 \text{ cal/mole}$$

$$k = 0.57 \text{ gmole}/(\text{sec})(\text{kg cat.})(^{\circ}K)$$

Partial pressures in the above rate expressions were represented in terms of conversion  $x$  through the stoichiometry of the reaction and the ideal gas law.

The low temperature reactor calculations were carried in two separate parts. First, the temperature and conversion in each of the five adiabatic reactors were determined. This portion was carried out by the LTS (low-temperature side) routine and the LTR (low-temperature reactor) routine as part of the overall material and energy balance program for the entire system. The flow chart for the LTR routine is given in Appendix C. It has been assumed that reaction reaches 99% of equilibrium in each reactor and that reactor effluents are cooled back to 420°C before entering the next reactor.

Second, the size (length) of each reactor was determined by a separate program LTRS (low temperature reactor sizing) which was run after all process balances were completed.

The calculational procedure used to model the low-temperature reactor was quite simple. The reaction-rate equation for the catalyst and temperature of the increment was selected. The rate of reaction per unit volume was calculated, and the length of the increment adjusted to make the temperature rise in the increment equal to a predetermined amount. The new bulk temperature and composition for the reaction mixture was calculated, and the procedure was repeated. When the temperature reached 454°C, the  $V_2O_5$  reaction rate constants changed. When the temperature reached 600°C, the platinum bed started. When the program calculated that equilibrium had been passed, it went back one increment and cut the incremental temperature rise in half. Calculations proceeded in this manner until the incremental temperature rise had been decreased to 0.5°C. This occurred when the gas was within 1.0°C of equilibrium.

The program then moved on to the next reactor, using the outlet composition of the previous reactor and an input-specified temperature as a starting point.

All of the variables and constants used in the LTR program are in MKS units.

APPENDIX C. FLOW CHARTS AND PROGRAM LISTINGS

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Subroutine	LTS	Low-temperature side material and energy balances (nighttime)	95	122
Subroutine	HTR	High-temperature (daytime) SO <sub>3</sub> - SO <sub>2</sub> reactor	96	126
Subroutine	LTR	Low-temperature (nighttime) SO <sub>2</sub> - SO <sub>3</sub> reactor	97	132
Subroutine	DIST	Distillation column	98	134
Subroutine	STC	Steam turbine	99	142
Subroutine	CLR	Condenser load. Calculates load for given flow and output temperature	100	148
Subroutine	CTR	Condenser temperature. Calculates temperature of outlet stream of an exchanger whose load is specified.	101	150
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Subroutine	FINDT	Stream temperature for a stream with given enthalpy.	103	156
Subroutine	RECOPY	Copies data of one record into another.	104	157
Function	TRKP	Equilibrium constant in terms of conversion of SO <sub>3</sub> to SO <sub>2</sub> (daytime).	104	158
Function	TKP	Equilibrium constant in terms of conversion of SO <sub>2</sub> to SO <sub>3</sub> (nighttime).	104	159
Function	CP	Specific heat of stream.	105	160
Function	DHR	Heat of reaction of SO <sub>3</sub> - SO <sub>2</sub> .	105	161

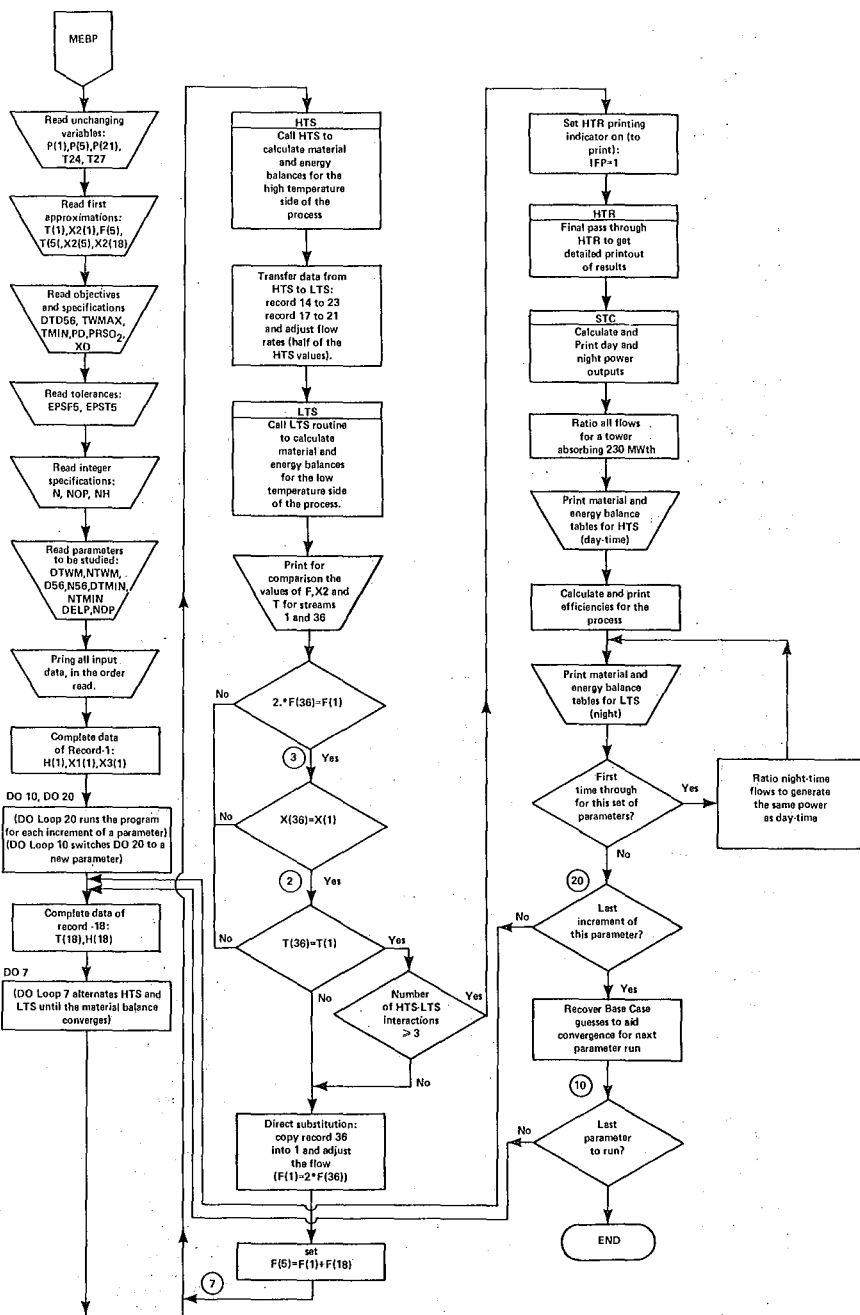


<u>Contents (Continued)</u>			<u>Page Number</u>	
			<u>Flowchart</u>	<u>Program</u>
Subroutine	ENTR1	Enthalpy of liquid mixture.	106	162
Subroutine	ENTR2	Enthalpy of gas mixture.	106	163
Subroutine	LHR	Latent heat.	107	164
Subroutine	VKCR	Volatility K constant.	107	165
Subroutine	BPTR	Bubble point temperature.	108	166

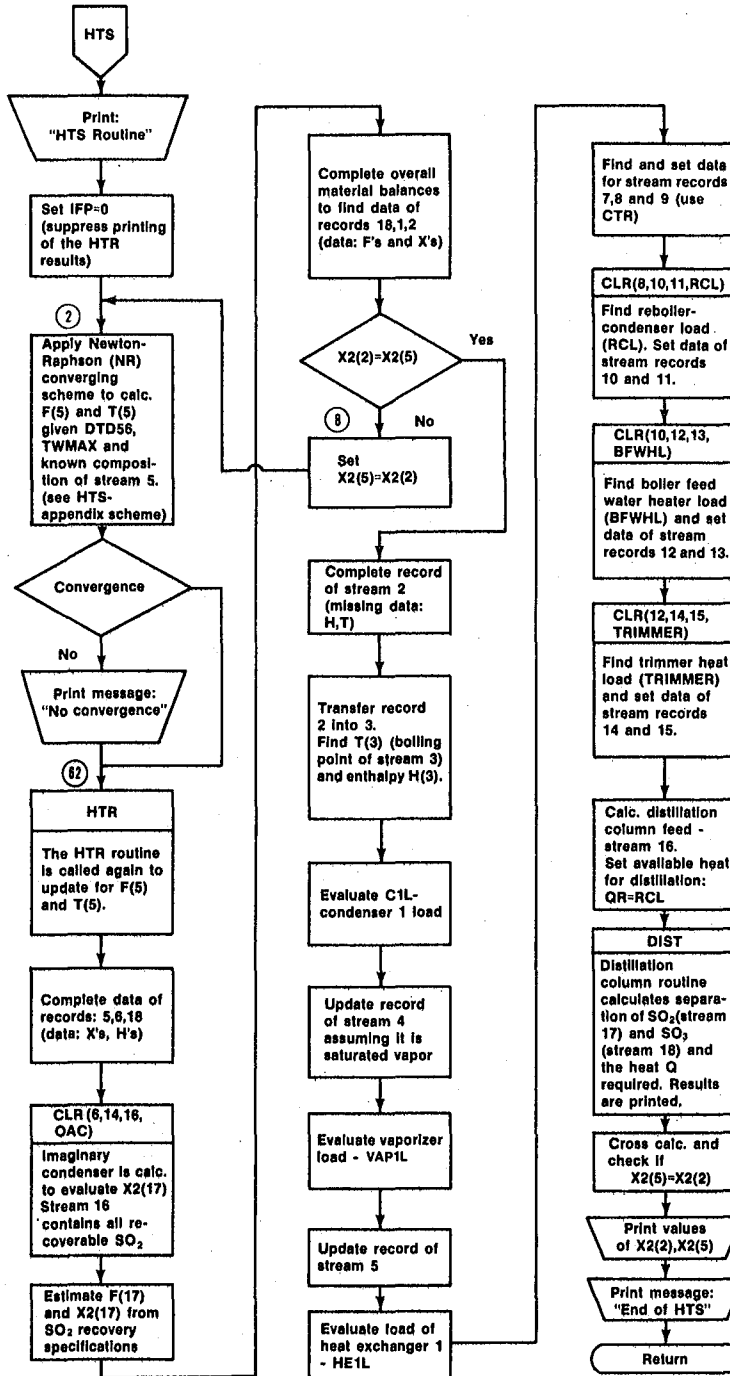
SAMPLE PRINTOUT OF RESULTS.

168

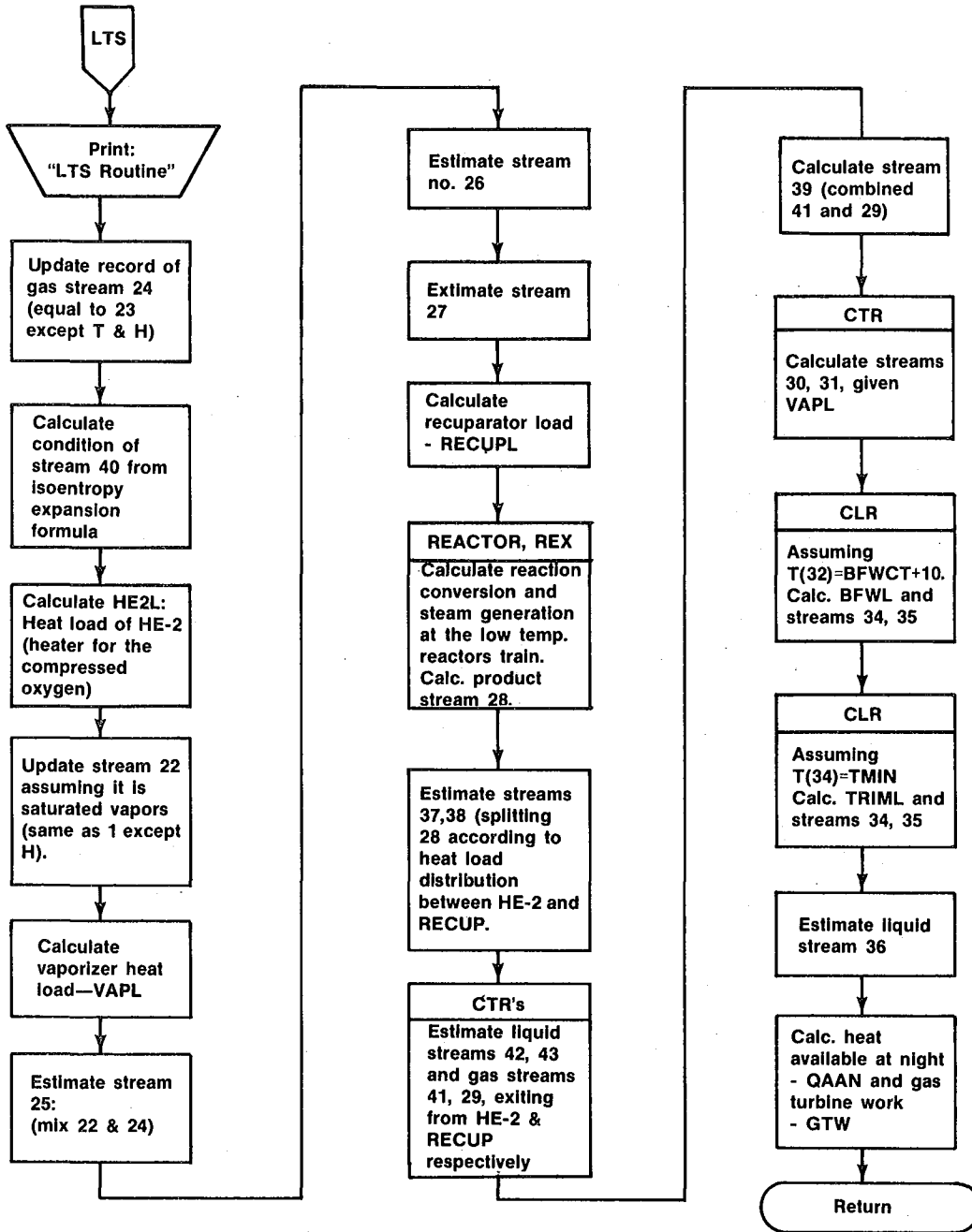
MEBP - Material and Energy Balances Program



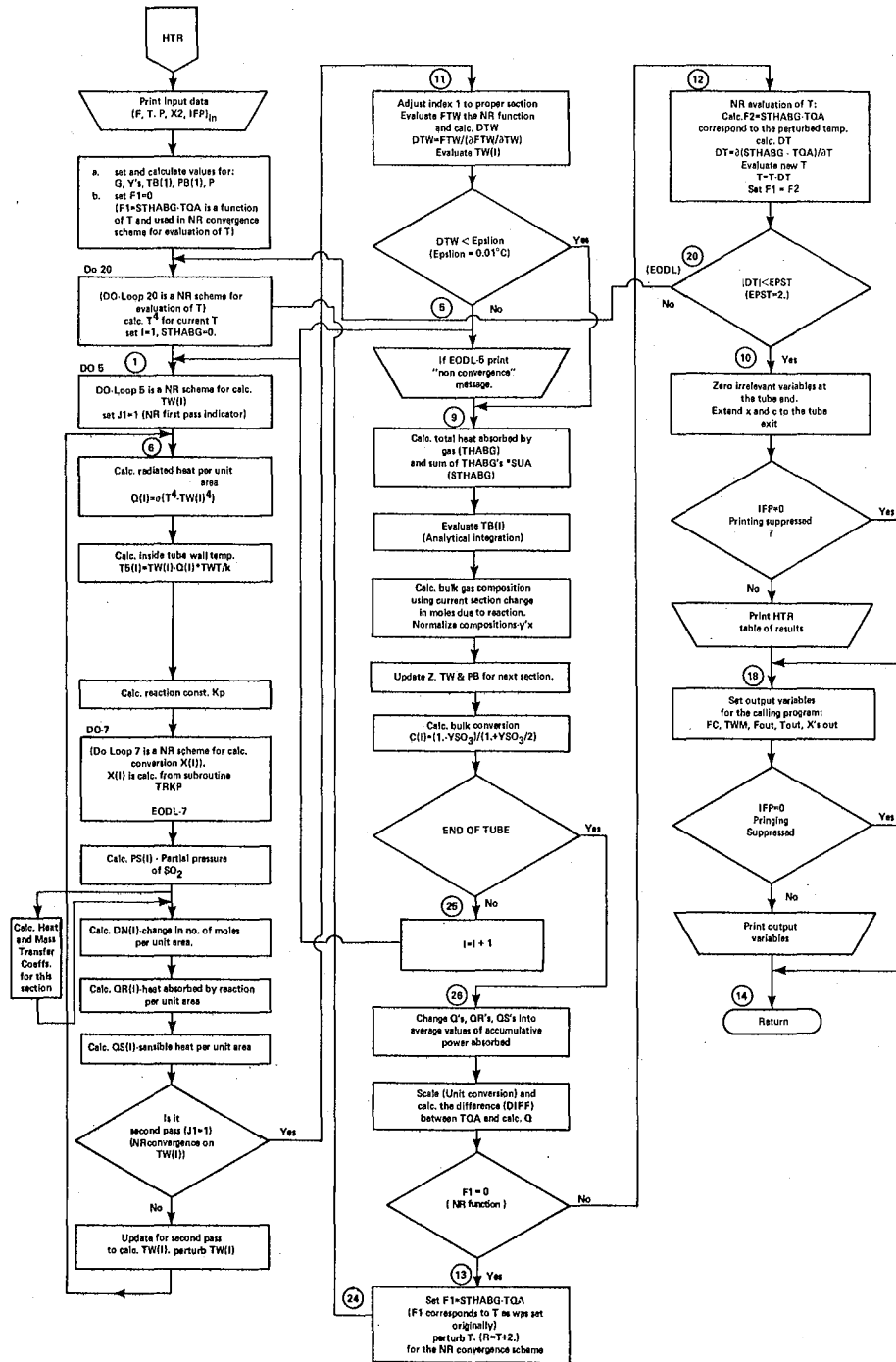
HTS -- High Temperature Side Routine



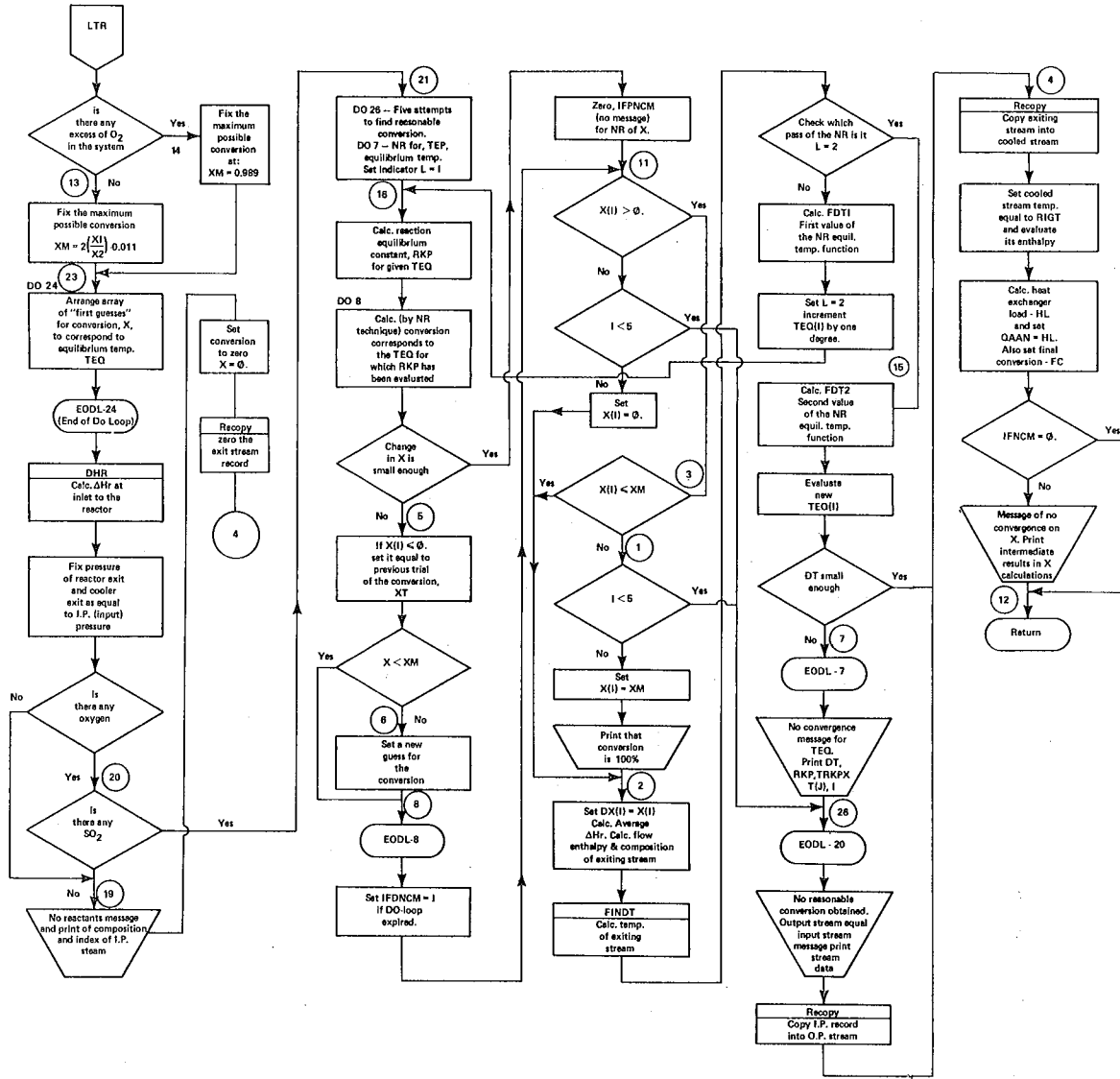
LTS — Low Temperature Side Material and Energy Balances Routine



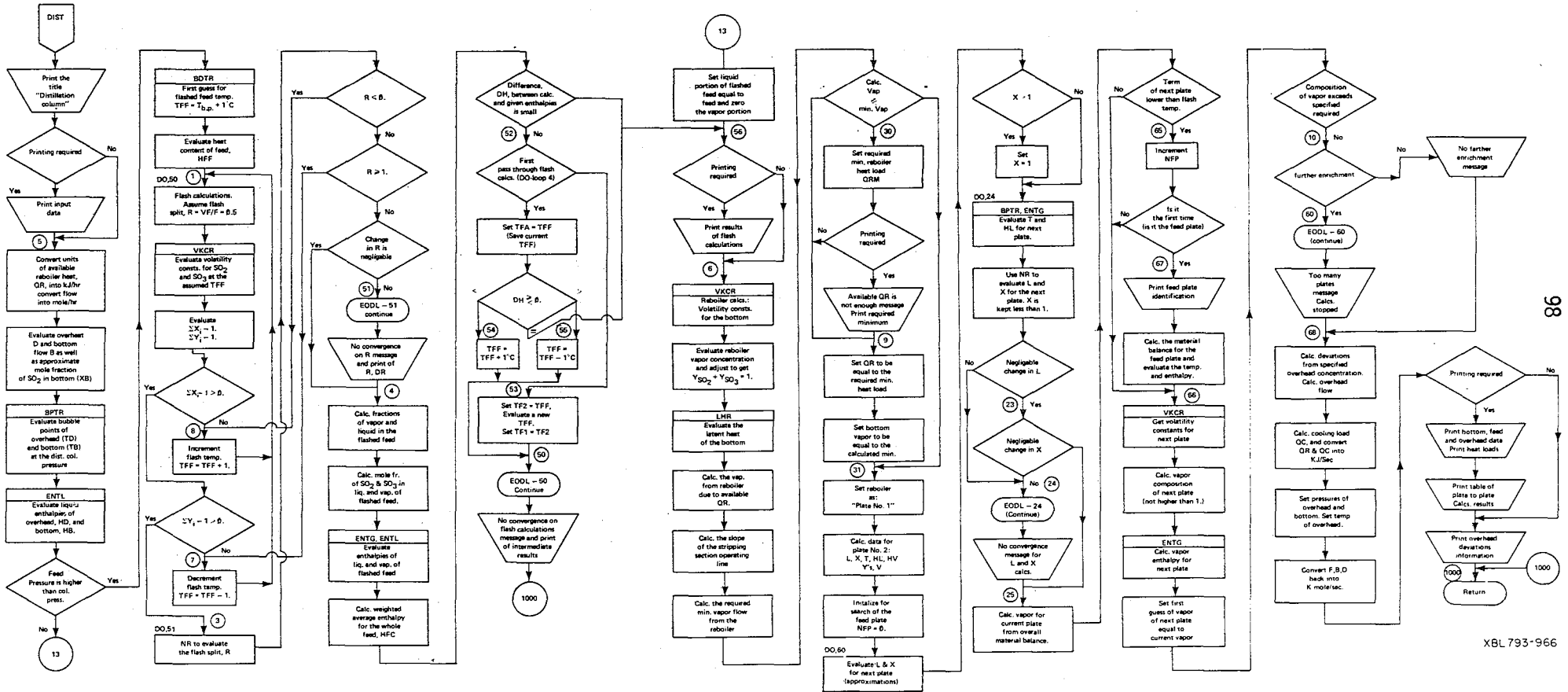
HTR - High Temperature Reactor Routine



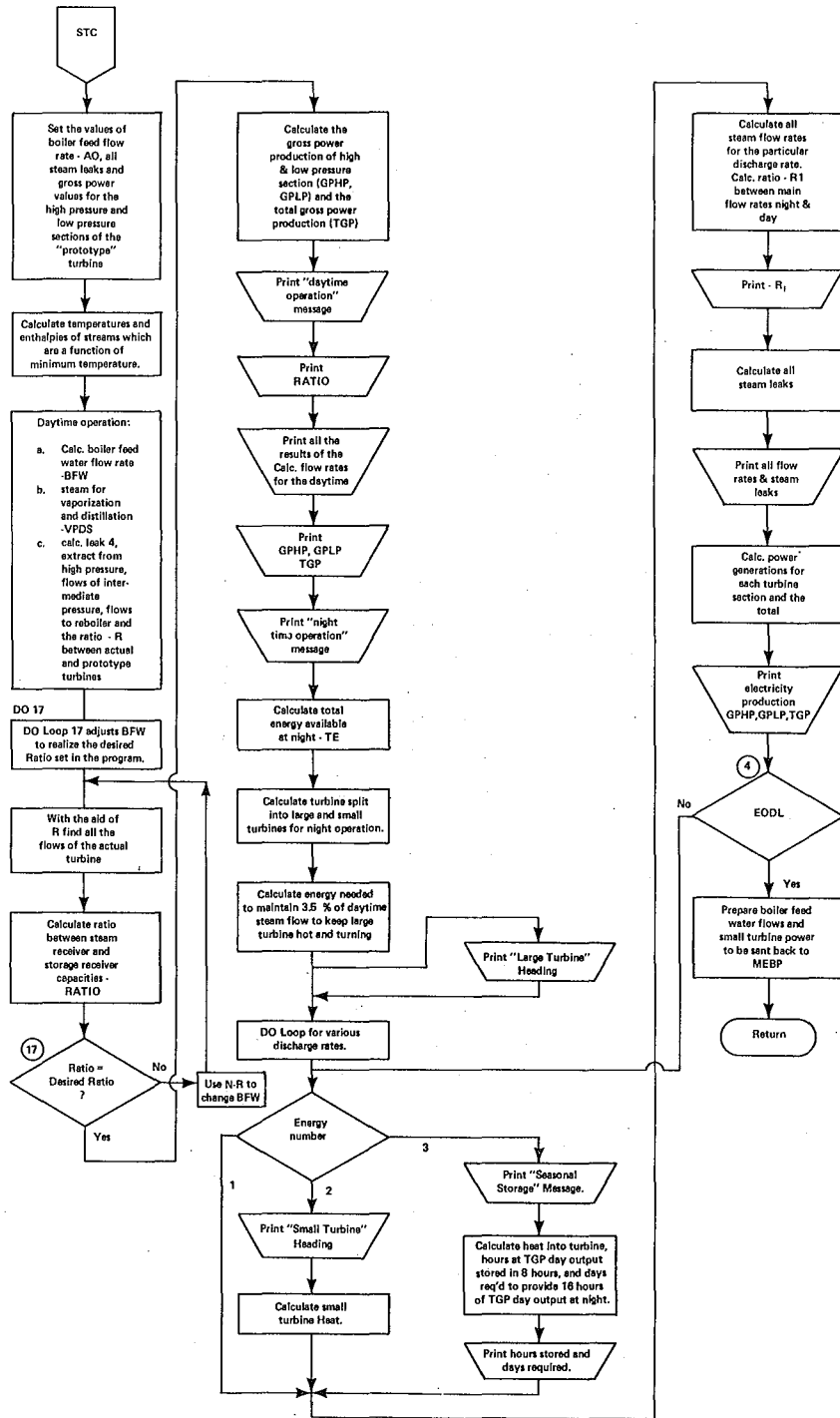
LTR - Low Temperature Routine



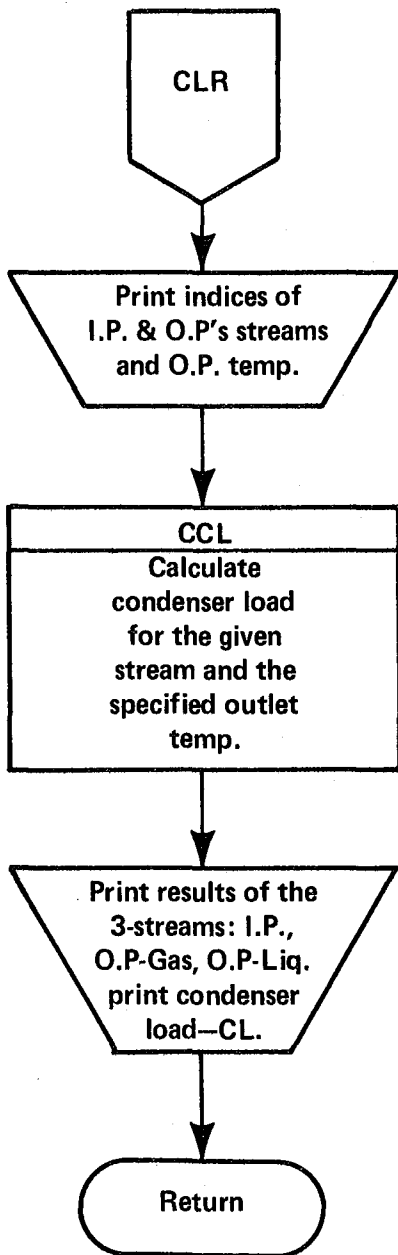
## Distillation Column Routine Flow Chart



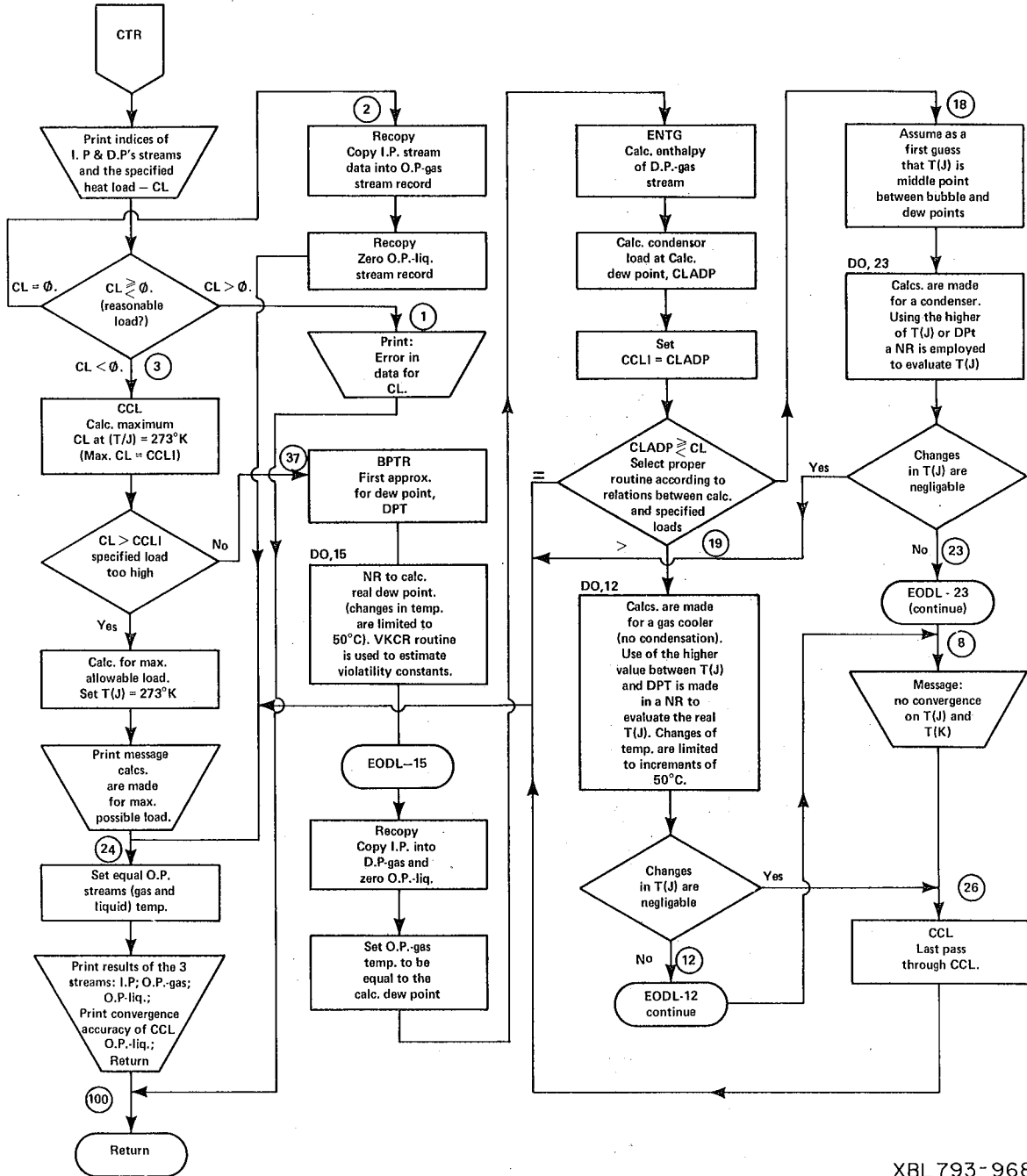
STC -- Steam Turbine Calculations Routine



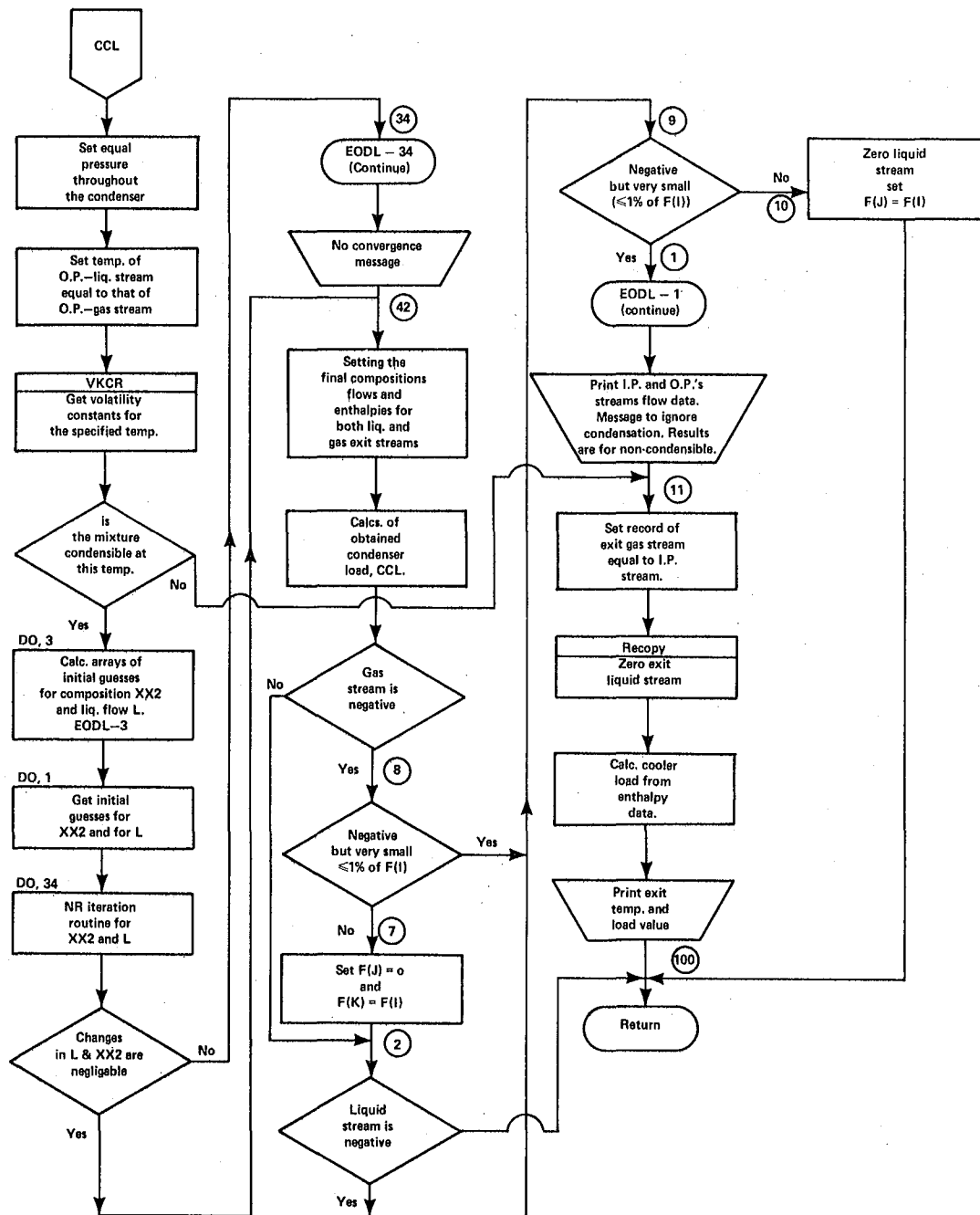


**CLR – Condenser  
Lead Routine**

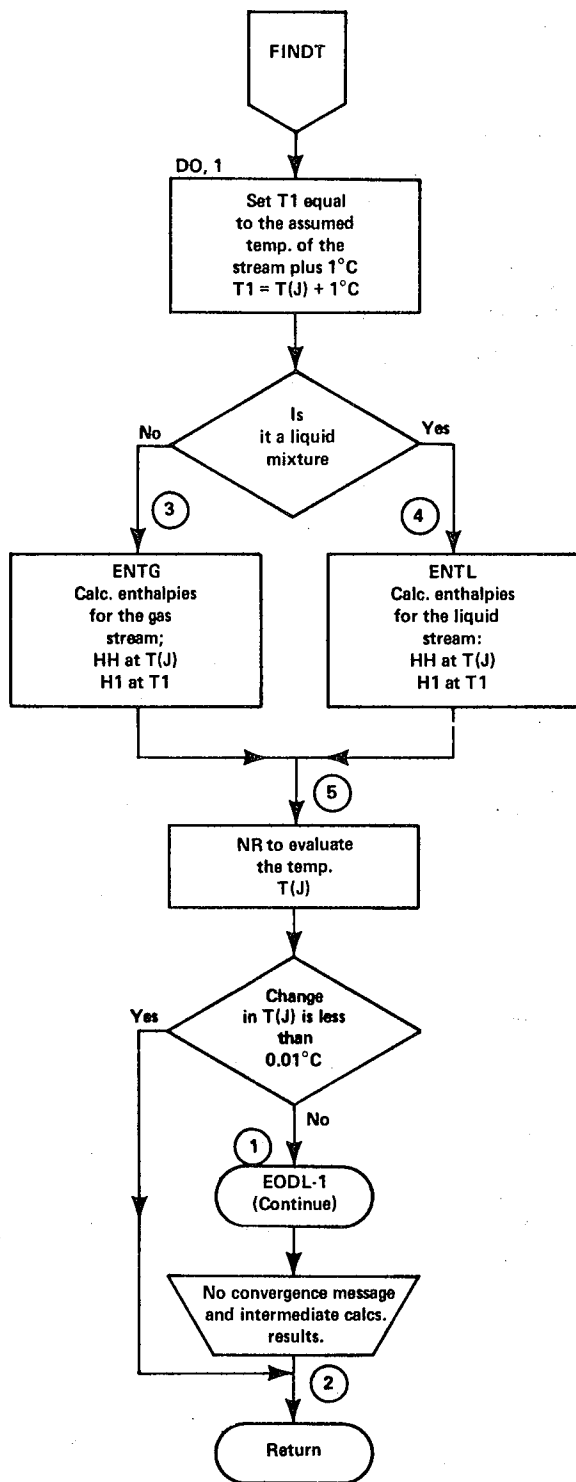
CTR - Condenser Temperature Routine



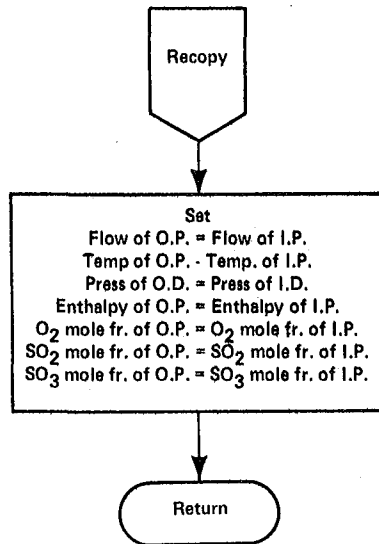
CCL - Calculation of Condenser Load



FINDT – Find Temperature of Stream Routine

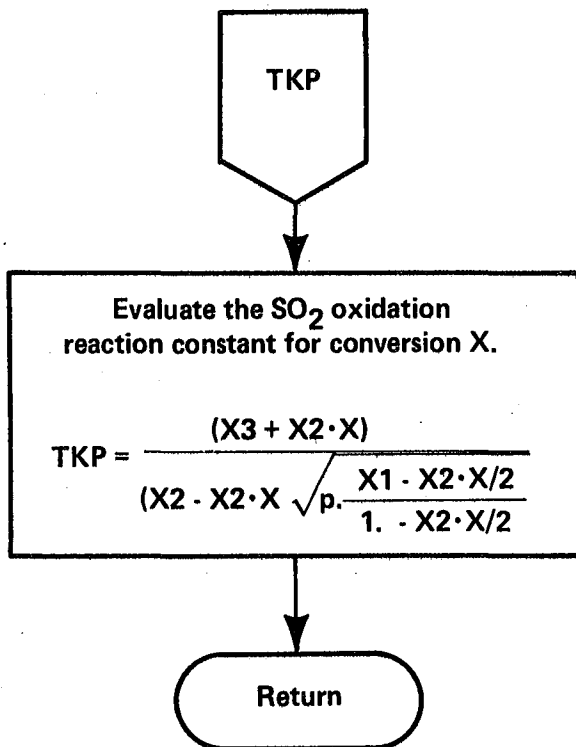


Recopy -recopy  
one record into  
another



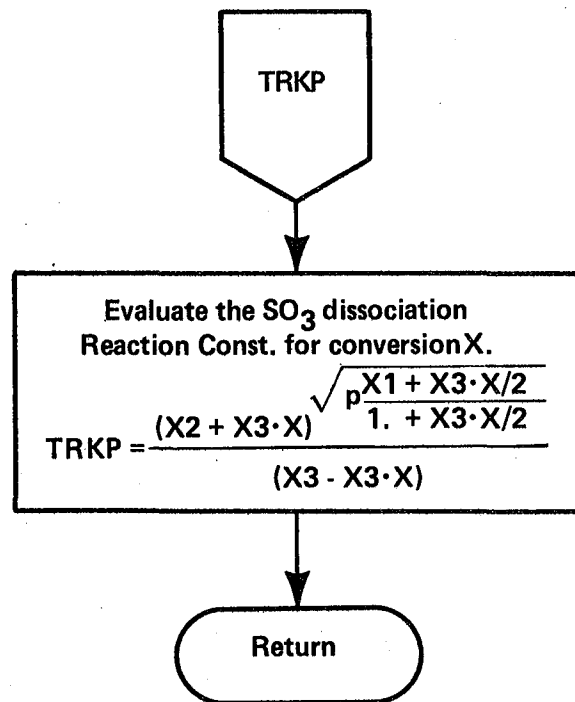
XBL 793-954

**TKP - SO<sub>2</sub> SO<sub>3</sub> Equilibrium  
Constant Function**



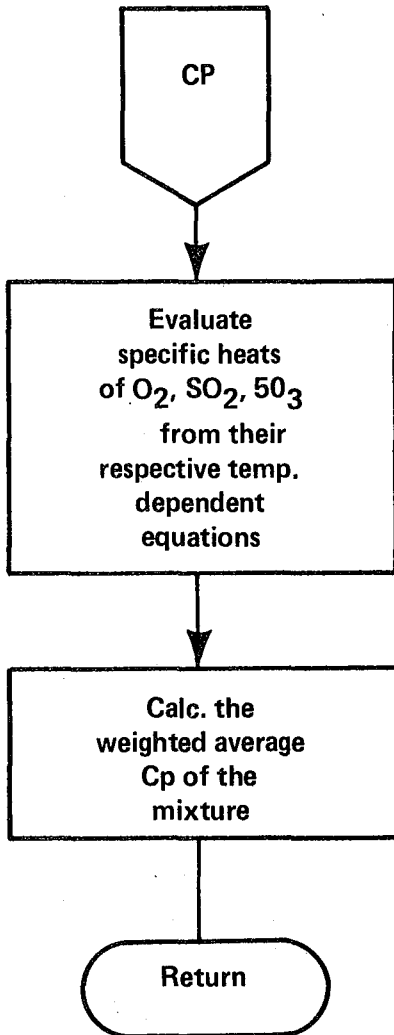
XBL 793-964

**TRKP - SO<sub>3</sub> SO<sub>2</sub> Equilibrium  
Constant Function**



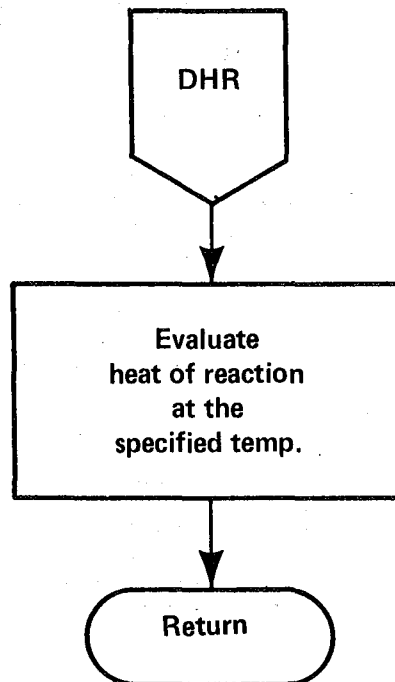
XBL 793-963

## CP – Specific Heat Function



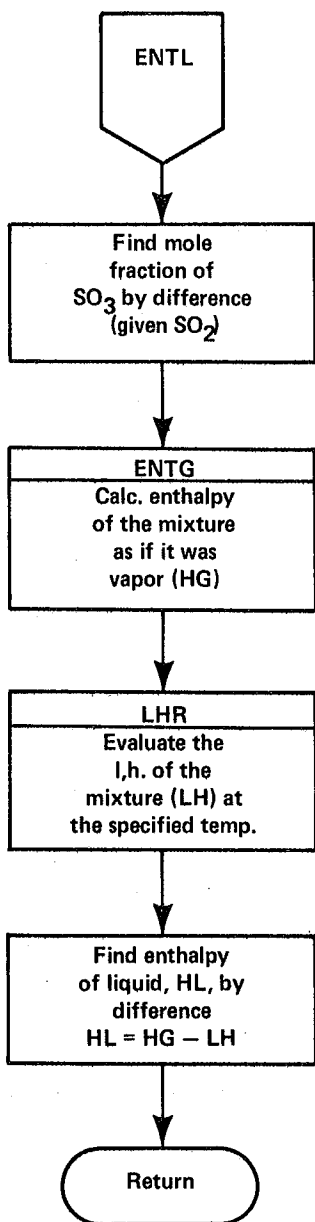
XBL 793-962

## DHR – Delta Heat of Reaction



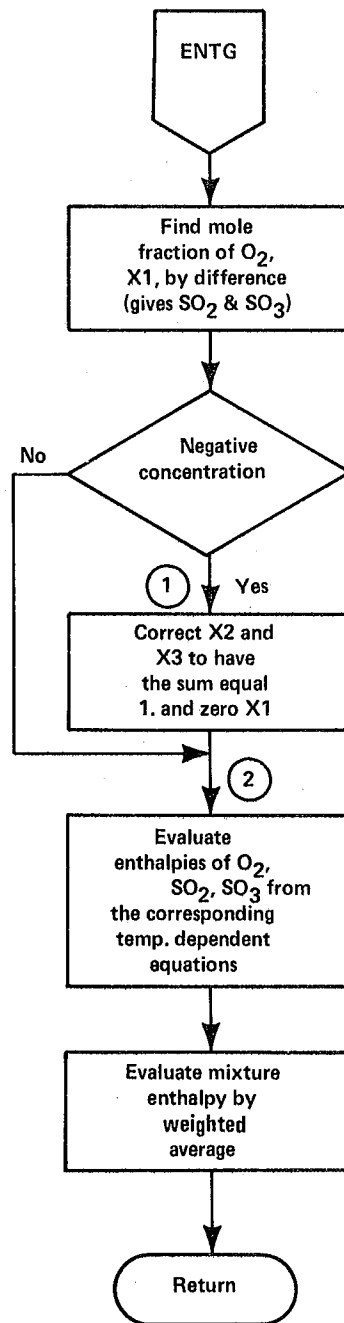
XBL 793-961

ENTL – Enthalpy of Liquid Mixture Routine



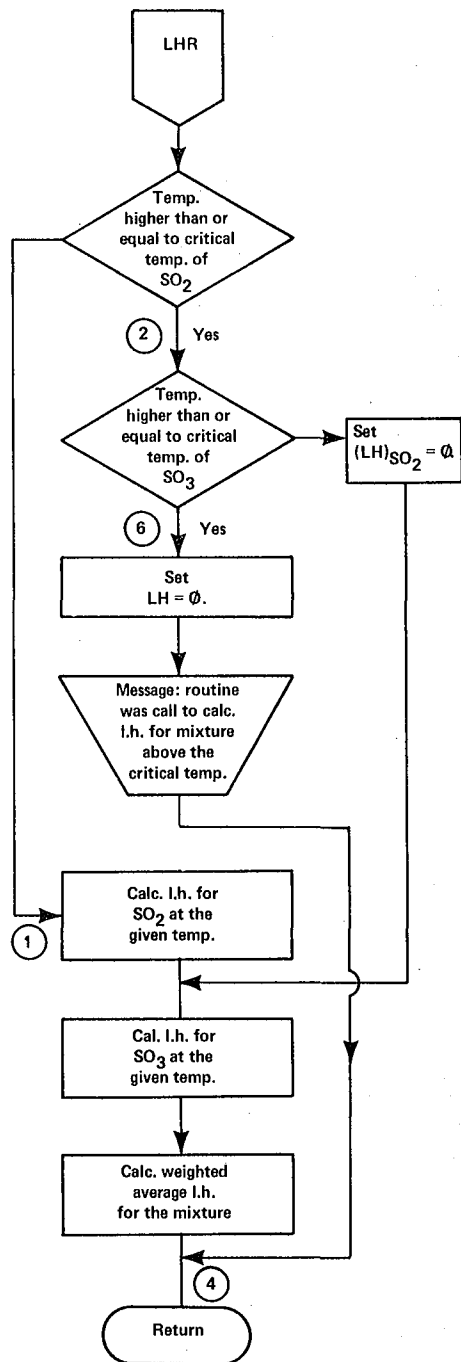
XBL 793 - 960

ENTG – Enthalpy of Gas Mixture Routine



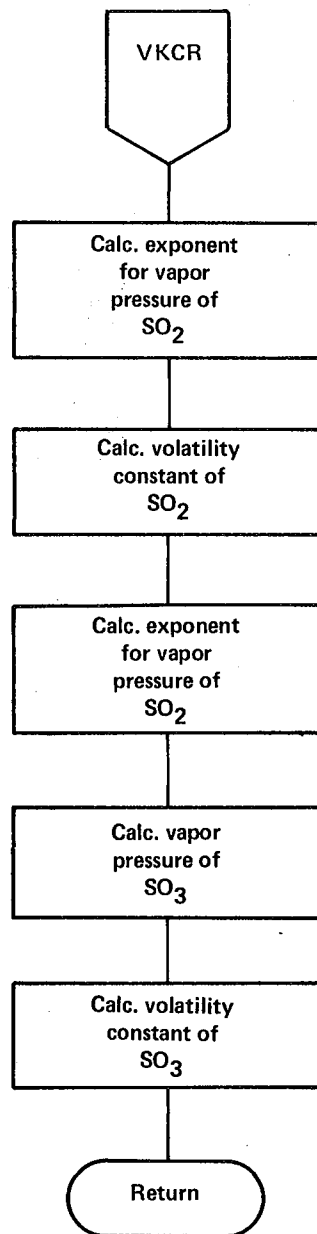
XBL 793 - 958

LHR – Latent Heat of Reaction Routine



XBL 793-959

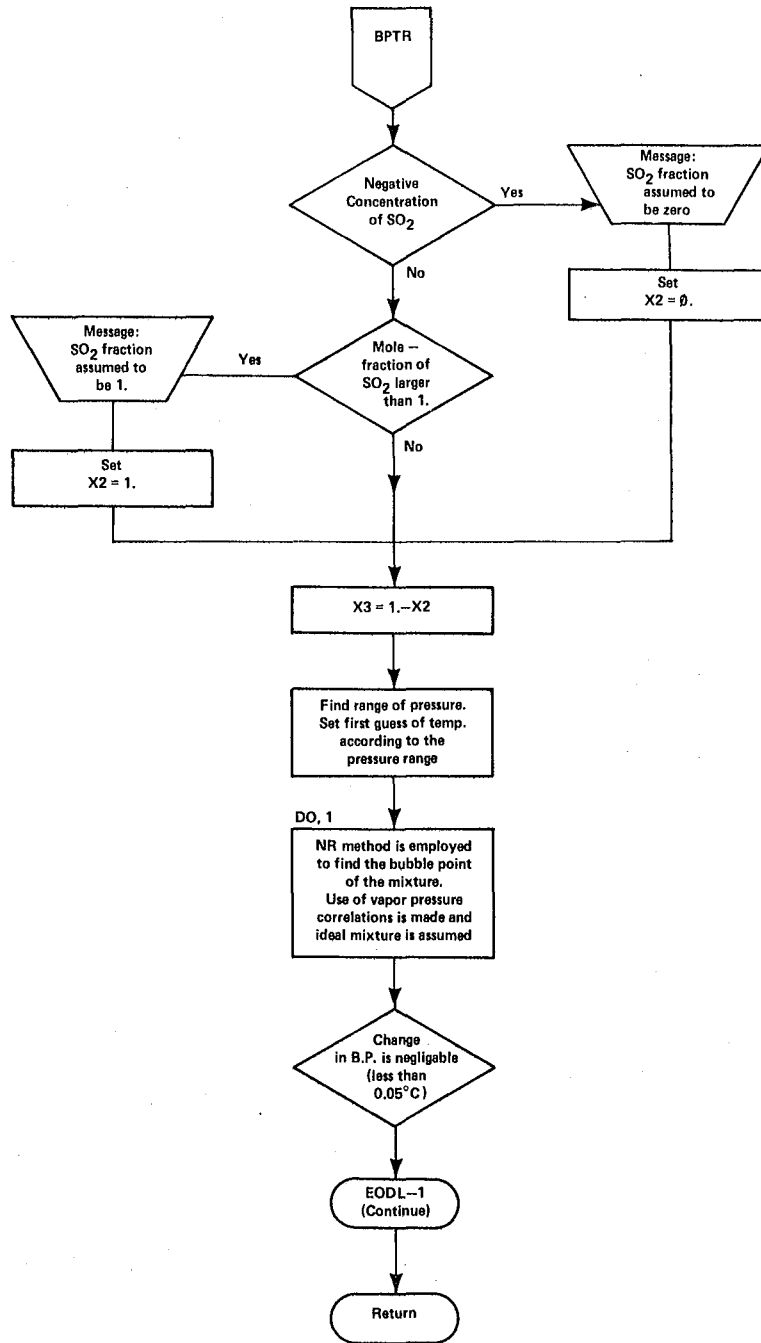
VKCR – Volatility K Constant Routine



XBL 793-952



BPTR - Bubble Point  
Temperature Routine



```

PROGRAM MEBP(INPUT,OUTPUT,PUNCH)                                MEBP 10
*****MEBP 20
*                                                                    *MEBP 30
*   UPDATED 2/28/78                                           *MEBP 40
*   MEBP - MATERIAL AND ENERGY BALANCES PROGRAM FOR CES     *MEBP 50
*                                                                    *MEBP 60
*****MEBP 70
*PROGRAM CALCULATES MATERIAL AND ENERGY BALANCES FOR THE CHEMICAL HEAT *MEBP 80
*STORAGE SYSTEM BASED ON S2,S02,S03. THE PROCESS IS DESIGNED TO SUPPLY *MEBP 90
*THE NECESSARY HEAT FOR A STEAM POWER PLANT DURING NIGHT TIME. DIRECT *MEBP 100
*STEAM GENERATION PLANT IS INTEGRATED WITH THE STORAGE SYSTEM TO PROVIDEMERP 110
*MAXIMUM HEAT EFFICIENCY FOR THE COMBINED PROCESS (SEE DAYAN ET AL , *MEBP 120
*PROCEEDING OF THE 12TH IECEC,P.1181,WASHINGTON DC 1977). *MEBP 130
*THE PROGRAM STARTS WITH READING BASIC DATA (SPECIFICATIONS,TOLERANCES,*MEBP 140
*TOTAL HEAT AVAILABILITY,ETC.) AND FIRST GUESSES FOR KEY STREAMS (THESE*MEBP 150
*ARE LATER UPDATED). THE PROGRAM USES TWO MAIN SUBROUTINES-HTS AND LTS *MEBP 160
*TO CALCULATE THE BALANCES FOR THE DAY AND NIGHT-TIME OPERATIONS RESPE-MEBP 170
*CTIVELY. DIRECT SUBSTITUTION IS USED FOR THE CYCLIC PROCESS UNTIL *MEBP 180
*CONVERGENCE ON FLOW, TEMP. AND COMPOSITION IS REACHED. THEN STC ROUTINEMEBP 190
*IS CALLED TO CALCULATE STEAM POWER PLANT GENERATION DATA. OUTPUT IS *MEBP 200
*SCALED AND PRINTED ACCORDING TO TQA-TOTAL HEAT AVAILABLE AT THE RECEIV-MEBP 210
*ER FOR THE STORAGE PROCESS. *MEBP 220
*                                                                    *MEBP 230
*THE FOLLOWING SUBROUTINES ARE BEING USED= *MEBP 240
*BPTR(P,X2,T) - BOILING POINT TEMP.T OF LIQ. MIX. OF S02-S03 AT P,X2 *MEBP 250
*CCL(TJ)-COMMON(TO CTR+CLR)FUNCTION TO CALC. CONDENSER LOAD AT EXIT T-TJMEBP 260
*CLR(IN,NG,NL,CL)-(CONDENSER LOAD CL, FOR INCOMING GAS STREAM NI AND *MEBP 270
*   OUTGOING GAS STREAM NG AND LIQ. STREAM NL. *MEBP 280
*CP(T,X1,X2,X3)-HEAT CAPACITY OF GAS MIX.(X1,X2,X3) AT TEMP. T *MEBP 290
*CTR(IN,NG,NL,CL)-CONDENSER EXIT STREAMS(NG,NL)TEMP. FOR GIVEN LOAD-CL *MEBP 300
*DHR(T)-HEAT OF REACTION AS FUNCTION OF TEMP. T *MEBP 310
*DIST(F,TF,PF,HF,XF,QR,XQ,P,PR,S2,N,D,TM,PD,HLM,YM,B,TB,PB,HB,XB)-PLATE*MEBP 320
*   TO PLATE CALC. OF DISTILLATION TOWER FOR BINARY MIX. S02-S03 *MEBP 330
*ENTR1(T,X2,HL)-ENTHALPY CALCS. FOR S02-S03 LIQ.MIX AT TEMP-T,COMPOS-X2*MEBP 340
*ENTR2(T,X2,X3,HG)-ENTHALPY CALCS. FOR S02-S02-S03 GAS MIX.AT T,X2,X3 *MEBP 350
*FINDT(NS,NF)-FIND TEMP. OF STREAM NF. NS=STREAM STATE=1-LIQ. 2-GAS *MEBP 360
*HTR(FI,TI,PI,X2I,FO,TO,PO,X1O,X2O,X3O,FC,TWM,IFP)-HIGH TEMP. RECEIVER-*MEBP 370
*   REACTOR. I-INPUT STREAM, O-OUTPUT STREAM,FINAL CONV.,TW-MAX,PRINT*MEBP 380
*HTS - MATERIAL AND ENERGY BALANCES FOR THE HIGH TEMP. SIDE *MEBP 390
*LHR(T,X2,LH)-LATENT HEAT OF S02-S03 MIX. AT TEMP.-T,COMPOSITION-X2 *MEBP 400
*LTR(X,Q,N-IN,N-OUT,N-COLD) LOW TEMP. REACTOR ROUTINE. (N=STREAM NO.) *MEBP 410
*LTS - MATERIAL AND ENERGY BALANCES FOR THE LOW TEMP. SIDE *MEBP 420
*RECOPY(IIN,IOUT)-COPY RECORD NO.-IIN INTO RECORD NO.-IOUT *MEBP 430
*STC(QAAN, R )-STEAM TURBINE CALC. DETERMINES STEAM POWER PLANT SIZE *MEBP 440
*   AND OPERATION RATES DURING DAY AND NIGHT (VARIOUS DISCHARGE RATES*MEBP 450
*TRKP(X,P)-CALC. TRIAL VALUE FOR REACTION EQUILIBRIUM CONSTANT-KP *MEBP 460
*VKCR(P,T,K2,K3)-VOLATILITY CONSTANTS K2,K3 FOR S02,S03 AT P AND T *MEBP 470
*                                                                    *MEBP 480
*NOMENCLATURE= (SEE PROCESS SCHEMES FOR DETAILS) *MEBP 490
*COMMON BLOCKS NAMES= *MEBP 500
*   LAHTV   LOW AND HIGH TEMP. VARIABLES *MEBP 510
*   HTHEL   HIGH TEMP. HEAT-EXCHANGERS LOADS *MEBP 520
*   HTV     HIGH TEMP. VARIABLES *MEBP 530
*   LTV     LOW TEMP. VARIABLES *MEBP 540

```

* LTHEL	LOW TEMP. HEAT-EXCHANGERS LOADS	*MEBP 550
* NWORK	NIGHT WORK	*MEBP 560
* STREAM	STREAM RECORDS NAME (F,P,T,H,X1,X2,X3)	*MEBP 570
* * * * *		*MEBP 580
* * * * *		*MEBP 590
* * * * *		*MEBP 600
* * * * *		*MEBP 610
* * * * *		*MEBP 620
* * * * *		*MEBP 630
* * * * *		*MEBP 640
* * * * *		*MEBP 650
* * * * *		*MEBP 660
* * * * *		*MEBP 670
* * * * *		*MEBP 680
* * * * *		*MEBP 690
* * * * *		*MEBP 700
* * * * *		*MEBP 710
* * * * *		*MEBP 720
* * * * *		*MEBP 730
* * * * *		*MEBP 740
* * * * *		*MEBP 750
* * * * *		*MEBP 760
* * * * *		*MEBP 770
* * * * *		*MEBP 780
* * * * *		*MEBP 790
* * * * *		*MEBP 800
* * * * *		*MEBP 810
* * * * *		*MEBP 820
* * * * *		*MEBP 830
* * * * *		*MEBP 840
* * * * *		*MEBP 850
* * * * *		*MEBP 860
* * * * *		*MEBP 870
* * * * *		*MEBP 880
* * * * *		*MEBP 890
* * * * *		*MEBP 900
* * * * *		*MEBP 910
* * * * *		*MEBP 920
* * * * *		*MEBP 930
* * * * *		*MEBP 940
* * * * *		*MEBP 950
* * * * *		*MEBP 960
* * * * *		*MEBP 970
* * * * *		*MEBP 980
* * * * *		*MEBP 990
* * * * *		*MEBP1000
* * * * *		*MEBP1010
* * * * *		*MEBP1020
* * * * *		*MEBP1030
* * * * *		*MEBP1040
* * * * *		*MEBP1050
* * * * *		*MEBP1060
* * * * *		*MEBP1070
* * * * *		*MEBP1080
* * * * *		*MEBP1090
* * * * *		*MEBP1100
* * * * *		*MEBP1110

```

* PRSO2 PERCENT RECOVERY OF SO2 IN THE DIST. COL. *MEBP1120
* P1 PRESSURE FOR STREAM 1 *MEBP1130
* P5 PRESSURE FOR STREAM 5 *MEBP1140
* P21 PRESSURE FOR STREAM 21 *MEBP1150
* Q ARRAY FOR HEAT AVAILABLE AT REACTORS HEAT-EXCHANGERS *MEBP1160
* QGAN Q AVAILABLE AT NIGHT (NWORK) - (KJ/S) *MEBP1170
* QR TOTAL Q REQUIRED IN REBOILER (KJ/S) *MEBP1180
* QRFS Q FOR REBOILER COMINR FROM STEAM (HTHEL) - (KJ/S) *MEBP1190
* R 100. / (GROSS STEAM TURBINE POWER PRODUCTION) *MEBP1200
* RATIO STEAM GENERATION-STORAGE RATIO (FROM STC) *MEBP1210
* RCL REBOILER-CONDENSER LOAD (HTHEL) - (KJ/S) *MEBP1220
* RECUPL RECUPERATOR LOAD (LTHEL) - (KJ/S) *MEBP1230
* STOP SMALL TURBINE OUTPUT (FROM STC) (MW) *MEBP1240
* SUM SUM OF BOILER FEED AND TRIMMER HEAT DUTIES *MEBP1250
* T TEMF. (K) *MEBP1260
* TGPD TOTAL GENERATED POWER DURING THE DAY (MW-E) *MEBP1270
* TMA ARRAY FOR TMIN$$ TO BE STUDIED *MEBP1280
* TMI FIRST LOOP TMIN *MEBP1290
* TMIN MIN. ACHIVABLE T ANYWHERE IN THE SYSTEM *MEBP1300
* TQA TOTAL Q AVAILABLE AT THE RECEIVER (HTR) - (MJ/S=MW) *MEBP1310
* TRIML TRIMMER LOAD (LTS) - (KJ/S) *MEBP1320
* TRIMMER TRIMMER LOAD (HTS) - (KJ/S) *MEBP1330
* TW MAX. TEMP. AT TUBE WALLS AS CALC. BY HTR - (K) *MEBP1340
* TWA ARRAY FOR TWMAX$$ TO BE STUDIED *MEBP1350
* TWMA FIRST LOOP TWMAX *MEBP1360
* TWMAX MAX. PERMISSABLE WALL TEMP. AT THE ABSORBER *MEBP1370
* T1 TEMPERATURE STREAM 1 (K) *MEBP1380
* T24 SPECIFIED T(24) FOR LTS - (K) *MEBP1390
* T27 SPECIFIED REACTOR IGNITION TEMP. FOR LTS - (K) *MEBP1400
* VAPL VAPORIZER LOAD (LTS) - (KJ/S) *MEBP1410
* VAP1L VAPORIZER LOAD (HTS) - (KJ/S) *MEBP1420
* X ARRAY FOR CONVERSIONS AT THE LTR$$ *MEBP1430
* XD SPECIFIED X2 AT THE DIST. COL. CONDENSER *MEBP1440
* X1 OXYGEN CONTENT (MOLE FRACTION) *MEBP1450
* X2 SO2 CONTENT (MOLE FR.) *MEBP1460
* X3 SO3 CONTENT (MOLE FR.) *MEBP1470
* X21 MOLE FRAC. SO2 IN STREAM 1 (FIRST APPROX.) *MEBP1480
* X25 MOLE FRAC. SO2 IN STREAM 5 (FIRST APPROX.) *MEBP1490
* X218 MOLE FRAC. SO2 IN STREAM 18 (FIRST APPROX.) *MEBP1500
* *MEBP1510
*****MEBP1520
*
COMMON/STREAM/F(60),P(60),T(60),H(60),X1(60),X2(60),X3(60) *MEBP1530
COMMON/LTV/N,T24,T27,Q(5),X(5),C *MEBP1540
COMMON/HTV/DTD56,EPST5,TWMAX, PD,PRSO2,XD,EPSF5,NH,NOP *MEBP1550
COMMON /LAHTV/BFWCT,TM?N *MEBP1560
COMMON/HTHEL/C1L,VAP1L,HE1L,RCL,BFWHL,TRIMMER,QRFS *MEBP1580
COMMON/LTHEL/RECUPL,VAPL,BFWL,TRIML,HE2L *MEBP1590
COMMON/NWORK/QGAN,GTW *MEBP1600
DIMENSION TWA(10),DTA(10),TMA(10),PHA(10) *MEBP1610
*KEEP RECORD 45 ZERO FOR VARIOUS PROGRAM USES. *MEBP1620
DATA F(45),P(45),T(45),H(45),X1(45),X2(45),X3(45)/7*0./ *MEBP1630
*ALL CALC. BASED ON A BOEING TYPE RECEIVER ABSORBING 230. MW-TH. *MEBP1640
DATA TQA/230./ *MEBP1650
*PARAMETERS FOR THE BASE CASE *MEBP1660
DATA BTMIN,BTMAX,BDT56,BP/333.,1153.,140.,40./ *MEBP1670
* *MEBP1680

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*SET ALL VARIABLES IN STREAM EQUAL TO ZERO
DO 8 I=1,60
  8 CALL RECOPY(45,I)
*
*READ UNCHANGING VARIABLES
  READ 45,P1,P5,P21,T24,T27
*READ FIRST APPROXIMATIONS TO BE UPDATED BY THE PROGRAM
  READ 45,T1,X21,F5,X25,X218
*  READ OBJECTIVE DATA AND SPECIFICATIONS
  READ 45,DT56,TWMA,TMI,PRS02,XD
*READ TOLERANCES AND INCREMENTS DELTAS.
  READ 45,EP5F5,EPST5
*READ INTEGER SPECIFICATIONS=N,NOP,NH
  READ 48,N,NOP,NH
*READ PARAMETERS TO BE STUDIED=
  READ 56,DTWM,NTWM,D56,N56,DTMIN,NTMIN
  READ 56,DEL5P,NDP
  READ 48,NOPL
*WRITE ALL INPUTS FOR THE RECORD
  PRINT 16
  PRINT46,P1,P5,P21,T24,T27
  PRINT 17,T1,X21,F5,X25,X218
  PRINT18,DT56,TWMA,TMI,PRS02,XD
  PRINT 19,EP5F5,EPST5
  PRINT 49,N,NOP,NH
  PRINT57,DTWM,NTWM,D56,N56,DTMIN,NTMIN
  PRINT 58,DEL5P,NDP
*PRELIMINARY CALCULATIONS, DATA PREPARATION AND FIRST ESTIMATES
*COMPLETE DATA OF F(1)
  P(1)=P1
  T(1)=T1
  X2(1)=X21
  CALL ENTRI(T(1),X2(1),H(1))
  X1(1)=0.0
  X3(1)=1.-X2(1)
*DO LOOPS FOR STUDIED PARAMETERS
  TMA(1)=TMI
  DO 14 K=2,10
    14 TMA(K)=TMA(K-1)+DTMIN
    DO 32 K=1,10
      TWA(K)=BTMAX
      DTA(K)=BDT56
    32 PHA(K)=BP
    NOSP=NTMIN
    DO 10 I=1,NOPL
      DO 20 K=1,NOSP
        TWMAX=TWA(K)
        DTD56=DTA(K)
        P(5)=PHA(K)
        TMIN=TMA(K)
        T(1)=T1
        X2(1)=X21
        F(5)=F5
        X2(5)=X25
        X2(18)=X218
      *PD ESTIMATED FROM KNOWN F(TI IN)
        PD=4.64E-4*EXP(.0303*T(1 IN)

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*MEBP1690
*MEBP1700
*MEBP1710
*MEBP1720
*MEBP1730
*MEBP1740
*MEBP1750
*MEBP1760
*MEBP1770
*MEBP1780
*MEBP1790
*MEBP1800
*MEBP1810
*MEBP1820
*MEBP1830
*MEBP1840
*MEBP1850
*MEBP1860
*MEBP1870
*MEBP1880
*MEBP1890
*MEBP1900
*MEBP1910
*MEBP1920
*MEBP1930
*MEBP1940
*MEBP1950
*MEBP1960
*MEBP1970
*MEBP1980
*MEBP1990
*MEBP2000
*MEBP2010
*MEBP2020
*MEBP2030
*MEBP2040
*MEBP2050
*MEBP2060
*MEBP2070
*MEBP2080
*MEBP2090
*MEBP2100
*MEBP2110
*MEBP2120
*MEBP2130
*MEBP2140
*MEBP2150
*MEBP2160
*MEBP2170
*MEBP2180
*MEBP2190
*MEBP2200
*MEBP2210
*MEBP2220
*MEBP2230
*MEBP2240
*MEBP2250

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```

*COMPLETE DATA OF F(18)
*T(18) UPDATED FROM KNOWN F(TMIN)
  T(18)=TMIN+50.*(TMIN-273.)/100.
  P(18)=PD
  CALL BPTR(P(18),X2(18),T(18))
  CALL ENTR1(T(18),X2(18),H(18))
  BFWCT=TMIN
  PRINT 44,TWMAX,TMIN,DTD56,P(5)
  DO 7 M=1,5
  CALL HTS
  CALL RECOPY(14,23)
  CALL RECOPY(17,21)
  F(23)=F(23)/2.
  F(21)=F(21)/2.
  P(21)=P21
  IF(F(21))31,31,29
*
29 CALL LTS
  PRINT 52,F(36),F(1),X2(36),X2(1),T(36),T(1)
  IF(ABS(2.*F(36)-F(1))-0.015)3,3,4
  3 IF(ABS(X2(1)-X2(36))-0.008)2,2,4
  2 IF(ABS(T(1)-T(36))-1.0)1,1,1
  1 IF(M-2.)4,4,21
  4 CALL RECOPY(36,1)
  P(1)=P1
  F(1)=2.*F(1)
  IF(F(21))31,31,12
31 PRINT 30,TMIN
  GO TO 10
12 F(5)=F(1)+F(18)
  P(5)=PHA(K)
  7 CONTINUE
  PRINT 22
*FINAL PASS THROUGH HTR
21 IFD=1
  PRINT 44,TWMAX,TMIN,DTD56,P(5)
  CALL HTR(F(5),T(5),P(5),X2(5),F(6),T(6),P(6),X1(6),X2(6),X3(6),FC,
  1TW,IFD)
  L=0
*CALL STEAM TURBINE CALC. ROUTINE
  PRINT 9
  SUM=BFWHL+TRIMMER
  CALL STC(QAAN,R,T(10),T(30),R4,RATIO,STOP,BFWN1,BFWN2,TGPD)
*ADJUST FOR AN INTEGRATED POWER PLANT WITH A RECEIVER ABSORBING 230 MW
  DO 11 J=1,18
  11 F(J)=F(J)*R
  C1L=C1L*R
  VAP1L=VAP1L*R
  HE1L=HE1L*R
  RCL=RCL*R
  TRIMMER=SUM*R-BFWHL
  QRFS=QRFS*R
  34 DO 36 J=21,60
  36 F(J)=F(J)*R
  DO 15 J=1,5
  15 Q(J)=Q(J)*R
  RECUPL=RECUPL*R

```

```

*MEBP2260
*MEBP2270
MEBP2280
MEBP2290
MEBP2300
MEBP2310
MEBP2320
MEBP2330
MEBP2340
MEBP2350
MEBP2360
MEBP2370
MEBP2380
MEBP2390
MEBP2400
MEBP2410
*MEBP2420
MEBP2430
MEBP2440
MEBP2450
MEBP2460
MEBP2470
MEBP2480
MEBP2490
MEBP2500
MEBP2510
MEBP2520
MEBP2530
MEBP2540
MEBP2550
MEBP2560
MEBP2570
MEBP2580
*MEBP2590
MEBP2600
MEBP2610
MEBP2620
MEBP2630
MEBP2640
*MEBP2650
MEBP2660
MEBP2670
MEBP2680
MEBP2690
MEBP2700
MEBP2710
MEBP2720
MEBP2730
MEBP2740
MEBP2750
MEBP2760
MEBP2770
MEBP2780
MEBP2790
MEBP2800
MEBP2810
MEBP2820

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VAPL=VAPL*R
BFWL=BFWN1
HE2L=HE2L*R
GTW=GTW*R
ATQA=ATQA*R
QAAN=QAAN*R
CALL CTR(30,32,33,BFWL)
CALL CLR(32,34,35,TRIML)
IF(L.GT.0) GO TO 35
*FINAL CALL FOR DIST. ROUTINE AND PRINTING ITS RESULTS.
PRINT 9
QR=RCL
CALL DIST(F(16),T(16),P(16),H(16),X2(16),QR, X0,PD,PRSO2,NOP,F(17)
1,T(17),P(17),H(17),X2(17),F(18),T(18),P(18),H(18),X2(18),IFP)
*
*PRINTOUT MATERIAL AND ENERGY BALANCES - HTS
PRINT 44,TWMAX,TMIN,DTD56,P(5)
PRINT 40
PRINT 41
PRINT 42
PRINT 54,(J,X1(J),X2(J),X3(J),T(J),P(J),F(J),H(J),J=1,NH)
PRINT 47,C1L,VAP1L,HE1L,RCL,BFWHL,TRIMMER,QRFS
*CALCULATE SEVERAL EFFICIENCIES WHICH DESCRIBE THE SYSTEM.
EOPAN=STOP*.97+GTW*.9/2./1000.
DYPR=.958*TGPD
E1=(DYPR+EOPAN*2.)/((RATIO+1.)*ATQA)
E2=DYPR/((RATIO*ATQA-VAP1L/1000.+BFWHL/1000.-QRFS/1000.))
EDAN=QAAN+BFWL+TRIML
E3=2.*EDAN/(ATQA*1000.+VAP1L-BFWHL+QRFS)
PRINT 37,E1,E2,E3
37 FORMAT(/3X,*SUMMARY OF EFFICIENCIES AT THE CHOSEN PARAMETERS*,//3X
1,4HE1= ,F6.4, /3X,4HE2= ,F6.4,/3X,4HE3= ,F6.4)
*PRINT RESULTS. LTS
35 PRINT53
PRINT 41
PRINT 42
PRINT 54,(J,X1(J),X2(J),X3(J),T(J),P(J),F(J),H(J),J=21,N)
PRINT50,RECUPL,VAPL,BFWL,TRIML,HE2L
PRINT 43,QAAN,GTW
PRINT 55,ATQA
PRINT 5
PRINT 42
PRINT 54,(J,X1(J),X2(J),X3(J),T(J),P(J),F(J),H(J),J=50,60)
PRINT 13,(J,Q(J), J=1,5),(X(J),J=1,5),C
*REPEAT LTS PRINTOUT FOR 100MW OUTPUT IF L IS GREATER THAN 0.
IF(L.GT.0) GO TO 33
R=R4
BFWN1=BFWN2
L=1
GO TO 34
33 PRINT 6
20 CONTINUE
*RECOVER BASE CASE GUESSES TO AID CONVERGENCE FOR OTHER PARAMETERS
IF(I-2)23,24,5
23 TWA(1)=TWMA
TMA(1)=BTMIN
DO 26 K=2,1J

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MEBP2830
MEBP2840
MEBP2850
MEBP2860
MEBP2870
MEBP2880
MEBP2890
MEBP2900
MEBP2910
*MEBP2920
MEBP2930
MEBP2940
MEBP2950
MEBP2960
*MEBP2970
*MEBP2980
MEBP2990
MEBP3000
MEBP3010
MEBP3020
MEBP3030
MEBP3040
*MEBP3050
MEBP3060
MEBP3070
MEBP3080
MEBP3090
MEBP3100
MEBP3110
MEBP3120
MEBP3130
MEBP3140
MEBP3150
MEBP3160
MEBP3170
MEBP3180
MEBP3190
MEBP3200
MEBP3210
MEBP3220
MEBP3230
MEBP3240
MEBP3250
MEBP3260
*MEBP3270
MEBP3280
MEBP3290
MEBP3300
MEBP3310
MEBP3320
MEBP3330
MEBP3340
*MEBP3350
MEBP3360
MEBP3370
MEBP3380
MEBP3390

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TWA(K)=DTMIN
26 TWA(K)=TWA(K-1)+DTMX
NOSP=NTMX
GO TO 10
24 DTA(1)=DT56
TWA(1)=BTMAX
DO 27 K=2,10
TWA(K)=BTMAX
27 DTA(K)=DTA(K-1)+D56
NOSP=N56
GO TO 10
25 IF(1.EQ.4)GO TO 10
PHA(1)=P5
DTA(1)=BDT56
DO 28 K=2,10
DTA(K)=BDT56
28 PHA(K)=PHA(K-1)-DELP
NOSP=NDP
10 CONTINUE
5 FORMAT(1H1,3X,*RESULTS OF THE LOW TEMP. REACTORS SYSTEM*)
6 FORMAT(3X,*F10 OF MEBP.*1)
9 FORMAT(1H1)
13 FORMAT(3X,5(140,I2,E10.4),/3X,5(1HX,F12.3),/3X,*LTR CONVERSION. C=
1*,F5.3)
16 FORMAT(/15X,*MEBP PROGRAM*/3X,*INPUT DATA*)
17 FORMAT(/3X,*FIRST APPROX=T(1),X2(1),F15), X2(5),X2(18)*,7F10.3
1)
18 FORMAT(/3X,*SPECIFICATION= DT56,TWMAX,TMIN,PRSO2,XD,*/3X,5F10.3)
19 FORMAT(/3X,*TOLERANCES= TSPF5,EPST5= *2F10.4)
22 FORMAT(3X,*MATERIAL BALANCE DIDNT CONVERGE.*)
30 FORMAT(3X,*F(36)=F(1)=0. NO CONDENSATION AT TMIN=*,F5.1,* GO TO N)
1XT TMAX*)
40)FORMAT(/3X,*TABLE-1,MATERIAL AND ENERGY DATA FOR THE DAYTIME HIGH
1)TEMPERATURE SIDE*,/3X,*STORAGE SYSTEM*)
41)FORMAT(/4X,*STREAM COMPOSITION (MOL PR.) TEMP. PRESSURE FLOW
1)ENTHALPY*)
42)FORMAT(7X,3HNO.,4X,2HO2,5X,3HSO2,5X,3HSO3,5X,3H(K),4X,*(BAR) (KVOL
1)/S)(KJ/KMOL)*)
43)FORMAT(/3X,*ENERGY PRODUCED AT NIGHT= GAAN=*,E11.4,3X,4HGTW=,E11.4
1,4H(KW))
44)FORMAT(1H1,2X,*PARAMETERS STUDIED= TWMAX=*,F6.1,2X,5HTMIN=,F5.1,2X
1,6HDT56=,F5.1,2X,5HPHTS=,F4.1)
45)FORMAT(10X,F10.3)
46)FORMAT(/3X,*NON-CHANGING DATA=P(1),P(5),P(21),T24,T27*,5F10.3)
47)FORMAT(/3X,*HEAT EXCHANGER LOAD (KW)=*,/3X,4HC1L=,F10.3,2X,6HVAP1L
1=,F10.3,3X,5HHE1L=,F10.3,3X,4HRCL=,F10.3,/3X,6HBFWHL=,F9.3,3X,8HTR
2)IMER=,F10.3,3X,5HQRFS=,F10.3)
48)FORMAT(10X,3I10)
49)FORMAT(/3X,*GENERAL= N=*,I3,3X,4HNOP=,I3,3X,3HNNH=,I2)
50)FORMAT(/3X,*HEAT EXCHANGERS LOAD (KW)=*,3X,6HRECUP=,F10.3,3X,4HVAP
1=,F10.3,/3X,4HBFW=,F10.3,3X,5HTRIM=,F10.3,2X,4HHE2=,F10.3)
52)FORMAT(/3X,*CALC. ARE REPEATED IF ANY OF THE FOLLOWING CONDS. IS
1)OT SATISFIED=*/3X,
2)IF(ABS(2.-F(36)-F(1))-0.015) F(36)=*,E11.5,3X,5HF(1)=,E11.5,/3X,*
3)IF(ABS(X2(1)-X2(36))-0.008) X(36)=*,E11.5,3X,5HX(1)=,E11.5,/3X,*
4)IF(ABS(T(1)-T(36))-1.0) T(36)=*,E11.5,3X,5HT(1)=,E11.5)
53)FORMAT(1H1,3X,*TABLE-2,MATERIAL AND ENERGY BALANCES FOR THE NIGHT

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1 TIME OPERATION OF*,/4X,*THE LOW TEMPERATURE SIDE*) MEBP3970
54 FORMAT(/2X,I6,3F8.2,2F8.2,F8.2,F9.1) MEBP3980
55 FORMAT(/3X,*RECEIVER LOAD TQA=*,F6.1,*(MW-THRM)*) MEBP3990
56 FORMAT(10X,3(F10.3,I10)) MEBP4000
57 FORMAT(3X,*INCREMENTS OF STUDIED PARAMS. TWMAX,DTD56,TMIN=*,3(F5.1MEBP4010
1,I3,2X)) MEBP4020
58 FORMAT(3X,*INCREMENTS OF STUDIED PARAMS. DELP, NDP=*,7X,F5.1,I3) MEBP4030
END MEBP4040
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SUBROUTINE HTS
*****
*   UPDATED 2/29/78
*   HTS -HIGH TEMP SIDE MATERIAL AND ENERGY BALANCES
*
*****
*RCUTINE IS CALLED BY MEBP TO CALC. MATERIAL AND ENERGY BALANCES FOR
*THE HIGH TEMP. SIDE (DAY-TIME OR CHARGING MODE) OF THE PROCESS.
*NO PARAMETERS ARE SPECIFIED IN THE CALL (COMMUNICATION BY COMMON BLOCK)
*THE FOLLOWING SUBROUTINES ARE BEING USED=
*BPTR(P,X2,T) - BOILING POINT TEMP.T OF LIQ. MIX. OF S02-S03 AT P,X2
*CLR(NI,NG,NL,CL)-CONDENSER LOAD CL, FOR INCOMING GAS STREAM NI AND
*   OUTGOING GAS STREAM NG AND LIQ. STREAM NL.
*CTR(NI,NG,NL,CL)-CONDENSER EXIT STREAMS(NG,NL)TEMP. FOR GIVEN LOAD-CL
*DIST(F,TF,PF,HF,XF,QR,XD,P,PRS02,N,D,TM,PD,HLM,YM,B,TB,PB,HB,XB)-PLATE
*   TO PLATE CALC. OF DISTILLATION TOWER FOR BINARY MIX. S02-S03
*ENTR1(T,X2,HL)-ENTHALPY CALCS. FOR S02-S03 LIQ.MIX AT TEMP-T,COMPOS-X2
*ENTR2(T,X2,X3,HG)-ENTHALPY CALCS. FOR O2-S02-S03 GAS MIX.AT T,X2,X3
*FINDT(NS,NF)-FIND TEMP. OF STREAM NF. NS=STREAM STATE=1-LIQ. 2-GAS
*HTR(FI,TI,PI,X2I,FO,TO,PO,X1O,X2O,X3O,FC,TWM,IFP)-HIGH TEMP. RECEIVER-
*   REACTOR. I-INPUT STREAM, O-OUTPUT STREAM,FINAL CONV.,TW-MAX,PRINT
*RECOPY(IIN,IOUT)-COPY RECORD NO.-IIN INTO RECORD NO.-IOUT
* NOMENCLATURE= (SEE PROCESS SCHEMES FOR DETAILS)
*COMMON BLOCKS NAMES=
*   LAHTV   LOW AND HIGH TEMP. VARIABLES
*   HTHEL   HIGH TEMP. HEAT-EXCHANGERS LOADS
*   HTV     HIGH TEMP. VARIABLES
*   STREAM  STREAM RECORDS NAME (F,P,T,H,X1,X2,X3)
*VARIABLES=
*   A       TERM IN THE J-MATRIX (NEWTON-RAPHSON METHOD)
*   ABSDX2  ABS. VALUE OF DIFF. BETWEEN X2(5) AND X2(2)
*   B       TERM IN THE J-MATRIX (NEWTON-RAPHSON METHOD)
*   BFWCT   ROILER FEED WATER CONDENSER TEMP. (K)
*   BFWHL   ROILER FEED WATER HEAT LOAD - HTS - (KJ/S)
*   C       TERM IN THE J-MATRIX (NEWTON-RAPHSON METHOD)
*   C1L     CONDENSER-1 LOAD (HTS) - (KJ/S)
*   D       TERM IN THE J-MATRIX (NEWTON-RAPHSON METHOD)
*   DET     DETERMINANT OF THE J-MATRIX (NR)
*   DF5     CORRECTION FOR F(5) (NR)
*   DTD56   DT DESIRED BETWEEN T(6) AND T(5) ,(K)
*   DT5     CORRECTION FOR T(5) (NR)
*   EPSF5   LIMITS FOR CONVERSION ON F(5)
*   EPST5   LIMITS FOR CONVERSION ON T(5)
*   F       FLOW(KMOL/SEC)
*   FC      FINAL CONVERSION IN REACTOR-RECEIVER (HTR)
*   FF      FLOW VARIABLE IN THE F-VECTOR (NR)
*   FT      TEMP VERIABLE IN THE F-VECTOR (NR)
*   F5      PERTUBED F(5) (F5=F(5)+0.5)
*   H       ENTHALPY,(KJ/KMOL)
*   HE1L   HEAT EXCHR. 1 LOAD (HTHEL) - (KJ/S)
*   I       RUNNING INDEX IN DO LOOP (NR)
*   IFP     INDICATOR FOR PRINTING (HTR) (0-NO,1-YES)

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```

T(5)=T(5)-DT5
PRINT 63,DF5,DT5
IF(ABS(DF5)-EPSF5)61,61,60
61 IF(ABS(DT5)-EPST5)62,62,60
60 CONTINUE
*IF LOOP COMPLETED NO CONVERGENCE ACHIEVED. PRINT MESSAGE.
PRINT 64
*UPDATE FOR FINAL F(5) AND T(5)
62 CALL HTR(F(5),T(5),P(5),X2(5),F(6),T(6),P(6),X1(6),X2(6),X3(6),FC,
1TW,IFP)
X3(5)=1.-X2(5)
X3(18)=1.-X2(18)
CALL ENTR2(T(6),X2(6),X1(6),H(6))
*OVER ALL MAT. BAL. TO CORRECT FOR X2(5). NOTE THAT T(16)=T(14)=TMIN
*ARE NOT THE FINAL RESULTS FOR THESE STREAMS.
T(14)=TMIN
CALL CLR(6,14,16,0AC)
F(17)=F(16)*X2(16)*PRSO2/XD
X2(17)=XD
F(18)=F(16)-F(17)
X2(18)=(F(16)*X2(16)-F(17)*X2(17))/F(18)
F(1)=F(5)-F(18)
F(2)=F(5)
P(2)=P(5)
X1(2)=0.
X2(2)=(F(1)*X2(1)+F(18)*X2(18))/F(2)
X3(2)=1.0-X2(2)
IF(L.EQ.1)GO TO 7
ABSDX2=ABS(X2(2)-X2(5))
IF(ABSDX2-0.1*X2(2))7,7,8
8 X2(5)=X2(2)
L=1
GO TO 2
7 H(2)=(F(1)*H(1)+F(18)*H(18))/F(2)
*FIND T(2). FIRST GUESS FOR T(2) IS (T(1)+T(18))/2
T(2)=(T(1)+T(18))/2.
CALL FINDT(1,2)
*PASSING THIS POINT IT IS ASSUMED THAT F(2) IS KNOWN.UPDATE FOR F(3)
CALL RECOPY(2,3)
*COND-1 HEATS SO3 STREAM TO ITS BOILING PT. T(3)=T(4).FIND IT
CALL BPTR(P(3),X2(3),T(3))
*ENTHALPY CHANGE BETWEEN H(2) AND H(3) EQUAL TO COND-1 HEAT LOAD (C1L)
CALL ENTR1(T(3),X2(3),H(3))
C1L=(H(3)-H(2))*F(3)
*UPDATE FOR F(4)
CALLRECOPY(3,4)
*VAPORIZER(VAP-1)LOAD IS CALC. FROM LATENT HEAT OR ENTHALPY CHANGE AT T4
CALL ENTR2(T(4),X2(4),X3(4),H(4))
VAP1L=(H(4)-H(3))*F(4)
*UPDATE FOR F(5) (ALL IS KNOWN BUT THERE MAY BE SOME SMALL DIFFERENCES
F(5)=F(4)
P(5)=P(4)
X1(5)=X1(4)
X2(5)=X2(4)
X3(5)=X3(4)
*HEAT LOAD AND TEMPS. OF HE-1 ARE FOUND WITH THE AID OF THE HIGH TEMP.
*REACTOR (HTR) ROUTINE RESULTS.

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CALL ENTR2(T(5),X2(5),X3(5),H(5))
HE1L=(H(5)-H(4))*F(5)
* CALC. CONDITIONS (T,H) OF F7. F(6)
*X1(6),X2(6),X3(6),P(6) WILL BE GIVEN BY HTR
*UPDATE FOR STREAM F7. FIND T7 BY EQUATING HE1L TO H7-H6.FIRST GUESS
*FOR T7 IS T(4)+DTD56
CALL RECOPY(6,7)
H(7)=H(6)-HE1L/F(7)
T(7)=T(4)+DTD56
CALL FINDT(2,7)
*CONTINUE HERE IF T7 CONVERGED OR ASSUME TO CONVERGED.
*ENTERING CONDENSATION ZONE. START WITH COND-1. KNOWING C1L,CALC. T(8)
CALL CTR(7,8,9,C1L)
*KNOWING CONDITIONS OF F8 REBOILER CALCS. ARE MADE.ASSUME T10=T18+10C
T(10)=T(18)+10.
CALL CLR(8,10,11,RCL)
*KNOWING CONDITIONS OF F10, BFW HEATE IS CALC. ASS.T12=T(STEAM COND)+10
T(12)=BFWCT+10.
CALL CLR(10,12,13,BFWHL)
*TRIMMER CALCULATIONS
CALL CLR(12,14,15,TRIMMER)
P(16)=P(15)
*CALC. DISTILLATION FEED CONDITIONS,I.F. F16=F9+F11+F13+F15
F(16)=F(9)+F(11)+F(13)+F(15)
X1(16)=0.
X2(16)=(F(9)*X2(9)+F(11)*X2(11)+F(13)*X2(13)+F(15)*X2(15))/F(16)
X3(16)=1.-X2(16)
H(16)=(F(9)*H(9)+F(11)*H(11)+F(13)*H(13)+F(15)*H(15))/F(16)
*FIRST GUESS OF T16 WAS SET=TMIN .NEWTON RAPHSON TECH. IS USED.
CALL FINDT(1,16)
*FIND DISTILLATION COL PRESJURE (CORESPONDING TO TMIN AT THE DIST.
*CONDENSER.)FIRST ASSUME PD AS READ AT THE DATA INPUT.
DO 14 I=1,10
IF(PD)18,18,19
18 PD=1.
GO TO 20
19 IF(PD-50.)20,20,21
21 PD=50.
20 CALL BPTR(PD,XD,TD1)
CALL BPTR(PD+0.1,XD,TD2)
FOP=TD1-TMIN
DFDP=10.*(TD2-TD1)
PD=PD-FOP/DFDP
IF(ABS(FOP/DFDP).LE.0.1)GO TO 16
14 CONTINUE
PRINT 15,PD,TD1
15 FORMAT(3X,*NO CONV. ON PD. PD=*,F6.3,3X,*TEMP. AT COND. IS=*,F5.1)
*CALL THE DISTILLATION ROUTINE
16 QR=RCL
CALL DIST(F(16),T(16),P(16),H(16),X2(16),QR, XD,PD,PRS02,NOP,F(17)
1,T(17),P(17),H(17),X2(17),F(18),T(18),P(18),H(18),X2(18),IFP)
*IF EXCESS HEAT IS AVAILABLE AT RCL PUSH IT DOWN TO BFW.
QRFS=QR-RCL
IF(QRFS)3,4,4
3 BFWHL=BFWHL-QRFS
QRFS=0.
*ADJUST FOR MISSING VARIABLES

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4 X1(17)=0. HTS 2240
  X1(18)=0. HTS 2250
  X3(17)=1.-X2(17) HTS 2260
  X3(18)=1.-X2(18) HTS 2270
*PASSING THIS PT. IT IS ASSUMED THAT ALL THE PROGRAM IS COMPLETED. *HTS 2280
*CHECK X2(2), AGAIN, TO SEE IF EQUAL TO X2(5). PRINT BOTH X2(2), X2(5) *HTS 2290
  F(1)=F(2)-F(18) HTS 2300
  X2(2)=(F(1)*X2(1)+F(18)*X2(18))/F(2) HTS 2310
  X3(2)=1.0-X2(2) HTS 2320
  PRINT 38, X2(2), X2(5) HTS 2330
*IF THERE IS NO MATCH IN X2(2) AND X2(5) IT SHOULD BE RECTIFIED AT 2ND PSHTS 2340
  PRINT 39 HTS 2350
  1 FORMAT(/3X, *HTS ROUTINE*) HTS 2360
  38 FORMAT(/3X, *OVERALL MAT. BAL. RESULTS IN X2(2) OF=*, F6.4, 3X, HTS 2370
  1 *COMPARE TO ASSUMED= *, F6.4, *HTS ROUTINE*) HTS 2380
  39 FORMAT(/3X, *END OF HTS RTN.*) HTS 2390
  63 FORMAT(/3X, *CONVERGENCE ON F(5) AND T(5)= DF5=*, E11.4, 3X, 4HDT5=, E1 HTS 2400
  11.4, *HTS ROUTINE*) HTS 2410
  64 FORMAT(/3X, *NO CONVERGENCE ON F(5) AND T(5) AT HTS ROUTINE.*) HTS 2420
  RETURN HTS 2430
  END HTS 2440

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SUBROUTINE LTS
*****LTS 10
* UPDATED 2/28/78 *LTS 20
* LTS - LOW TEMP. SIDE, MATERIAL AND ENERGY BALANCES. *LTS 30
* *LTS 40
* *LTS 50
*****LTS 60
*ROUTINE IS CALLED BY MEBP. COMMUNICATION IS DONE THROUGH COMMON BLOCKS.*LTS 70
* ROUTINE CALC. MATERIAL AND ENERGY BALANCES FOR THE LOW TEMP. SIDE. *LTS 80
* SCHEME INCLUDES GAS TURBINE FOR THE EX7A5S905 6F 62 16U33ET TEMP. - *LTS 90
* (T24 IS SPECIFIED). *LTS 100
*REACTOR INLET TEMP. T27=IGNITION TEMP. IS SPECIFIED. *LTS 110
*REACTOR ROUTINE CALCS. QAAN - Q TO STEAM AT NIGHT AND THE FINAL CONVER-LTS 120
*SION - FC. REX CALCS. THE CONDITIONS OF STREAM 28. *LTS 130
* *LTS 140
*THE FOLLOWING SUBROUTINES ARE BEING USED= *LTS 150
*CLR(NI,NG,NL,CL)-CONDENSER LOAD CL, FOR INCOMING GAS STREAM NI AND *LTS 160
* OUTGOING GAS STREAM NG AND LIQ. STREAM NL. *LTS 170
*CTR(NI,NG,NL,CL)-CONDENSER EXIT STREAMS(NG,NL)TEMP. FOR GIVEN LOAD-CL *LTS 180
*DHR(T)-HEAT OF REACTION AS FUNCTION OF TEMP. T *LTS 190
*ENTR2(T,X2,X3,HG)-ENTHALPY CALCS. FOR O2-SO2-SO3 GAS MIX. AT T,X2,X3 *LTS 200
*FIND(NS,NF)-FIND TEMP. OF STREAM NF. NS=STREAM STATE=1-LIQ. 2-GAS *LTS 210
*LTR(X,Q,N-IN,N-OUT,N-COLD) LOW TEMP. REACTOR ROUTINE. (N=STREAM NO.) *LTS 220
*RECOPY(IIN,IOUT)-COPY RECORD NO.-IIN INTO RECORD NO.-IOUT *LTS 230
* *LTS 240
*NOMENCLATURE= (SEE PROCESS SCHEMES FOR DETAILS) *LTS 250
*COMMON BLOCKS NAMES= *LTS 260
* LAHTV LOW AND HIGH TEMP. VARIABLES *LTS 270
* LTV LOW TEMP. VARIABLES *LTS 280
* LTHEL LOW TEMP. HEAT-EXCHANGERS LOADS *LTS 290
* NWORK NIGHT WORK *LTS 300
* STREAM STREAM RECORDS NAME (F,P,T,H,X1,X2,X3) *LTS 310
*VARIABLES= *LTS 320
* BFWCT BOILER FEED WATER CONDENSER TEMP. (K) *LTS 330
* BFWL BOILER FEED WATER HEAT LOAD - LTS - (KJ/S) *LTS 340
* C TOTAL CONVERSION FOR THE LTR SYSTEM *LTS 350
* CMBC COMBINED CONDENSER HE2+RECUP *LTS 360
* DHRA DHR AT AVERAGE TEMP. OF REACTOR OPERATION *LTS 370
* DT TEMP. DEVIATION OF STREAM J-2 FROM 693K *LTS 380
* F FLOW(KMOL/SEC) *LTS 390
* GTW GAS TURBINE WORK (NWORK) - (KJ/S) *LTS 400
* H ENTHALPY,(KJ/KMOL) *LTS 410
* HE2L HEAT EXCHR. 2 LOAD (LTHEL) - (KJ/S) *LTS 420
* I INDEX IN VARIOUS DO LOOPS *LTS 430
* J DEFINED AS (50+2*I) IN LTR$S DO LOOP *LTS 440
* N NO. OF STREAMS *LTS 450
* P PRESSURE(BAR) *LTS 460
* Q ARRAY FOR HEAT AVAILABLE AT REACTORS HEAT-EXCHANGERS *LTS 470
* QAAN Q AVAILABLE AT NIGHT (NWORK) - (KJ/S) *LTS 480
* QRF$ Q FOR REBOILER COMINR FROM STEAM (HTHEL) - (KJ/S) *LTS 490
* RECUPL RECUPERATOR LOAD (LTHEL) - (KJ/S) *LTS 500
* T TEMP.(K) *LTS 510
* TMIN MIN. ACHIEVABLE T ANYWHERE IN THE SYSTEM *LTS 520

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7 CALL RECOPY(45,I)
DO 8 I=1,5
8 Q(I)=0.
*CALL LTR TO CALC. ALL LOW TEMP. REACTORS
CALL RECOPY(27,50)
DO 1 I=1,5
J=50+2*I
CALL LTR(X(I),Q(I),J-2,J-1,J)
IF(T(J-1)-773.)2,10,3
2 DT=(773.-T(J-1))*(T(J-3)-693.)/(T(J-3)-T(J-1))
T(J-2)=693.+DT
CALL ENTR2(T(J-2),X2(J-2),X3(J-2),H(J-2))
Q(I-1)=F(J-2)*(H(J-3)-H(J-2))
CALL LTR(X(I),Q(I),J-2,J-1,J)
10 Q(I)=0.
CALL RECOPY(45,J)
CALL RECOPY(J-1,60)
GO TO 4
3 IF(I.LT.5)GO TO 1
T(60)=773.
CALL ENTR2(773.,X2(60),X3(60),H(60))
Q(I)=F(60)*(H(59)-H(60))
1 CONTINUE
*GET STREAM 28 AND QAAN FROM REACTOR ROUTINE.
4 QAAN=0.
DO 11 I=1,5
11 QAAN=QAAN+Q(I)
*FINAL CONVERSION CALCULATIONS
C=(X2(50)-X2(60))/X2(50)/(1.-X2(60)/2.)
*UPDATE REACTOR SYSTEM OUTPUT STREAM NO.28
CALL RECOPY(60,28)
*CALC. STREAMS 37 AND 38. F WILL BE LATER UPDATED.
CALL RECOPY(28,37)
CALL RECOPY(28,38)
CMBC=HE2L+RECUP
CALL CTR(28,29,43,CMBC)
F(37)=F(28)*HE2L/CMBC
F(38)=F(28)-F(37)
*RECALC. HE2 AS A CONDENSER STANDING BY ITSELF.
CALL CTR(37,41,42,HE2L)
*CALC. STREAMS 29 AND 43.
CALL CTR(38,29,43,RECUP_)
*CALC. STREAM 39. FIRST GUESS FOR T(39) IS (T(29)+T(41))/2.
F(39)=F(41)+F(29)
P(39)=P(29)
X1(39)=(X1(29)*F(29)+X1(41)*F(41))/F(39)
X2(39)=(X2(29)*F(29)+X2(41)*F(41))/F(39)
X3(39)=1.-X1(39)-X2(39)
H(39)=(H(29)*F(29)+H(41)*F(41))/F(39)
T(39)=(T(29)+T(41))/2.
CALL FINDT(2,39)
*CALC. STREAMS 30 AND 31.
CALL CTR(39,30,31,VAPL)
*CALC. STREAMS 32 AND 33
T(32)=BFWCT+10.
CALL CLR(30,32,33,BFWL)
*CALC. STREAMS 34,35.

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LTS 1100
LTS 1110
LTS 1120
*LTS 1130
LTS 1140
LTS 1150
LTS 1160
LTS 1170
LTS 1180
LTS 1190
LTS 1200
LTS 1210
LTS 1220
LTS 1230
LTS 1240
LTS 1250
LTS 1260
LTS 1270
LTS 1280
LTS 1290
LTS 1300
LTS 1310
LTS 1320
*LTS 1330
LTS 1340
LTS 1350
LTS 1360
*LTS 1370
LTS 1380
*LLTS 1390
LTS 1400
*LLTS 1410
LTS 1420
LTS 1430
LTS 1440
LTS 1450
LTS 1460
LTS 1470
*LLTS 1480
LTS 1490
*LLTS 1500
LTS 1510
*LLTS 1520
LTS 1530
LTS 1540
LTS 1550
LTS 1560
LTS 1570
LTS 1580
LTS 1590
LTS 1600
*LLTS 1610
LTS 1620
*LLTS 1630
LTS 1640
LTS 1650
*LLTS 1660

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T(34)=TMIN	LTS 1670
CALL CLR(32,34,35,TRI,IL)	LTS 1680
*CALC. STREAM 36. FIRST GUESS FOR T(36) IS (T(31)+T(33))/2.	*LTS 1690
P(36)=P(35)	LTS 1700
F(36)=F(31)+F(33)+F(35)+F(42)+F(43)	LTS 1710
X1(36)=0.	LTS 1720
X2(36)=(F(31)*X2(31)+F(33)*X2(33)+F(35)*X2(35)+F(42)*X2(42)+F(43)*X2(43))/F(36)	LTS 1730
X3(36)=1.-X2(36)	LTS 1740
H(36)=(F(31)*H(31)+F(33)*H(33)+F(35)*H(35)+F(42)*H(42)+F(43)*H(43))/F(36)	LTS 1750
T(36)=(T(31)+T(33))/2.	LTS 1760
CALL FINDT(1,36)	LTS 1770
*CALC. GAS TURBINE WORK.	LTS 1780
GTW=(H(24)-H(40))*F(24)	*LTS 1800
PRINT 5	LTS 1810
5 FORMAT(/3X,*END OF LTS RTN.*)	LTS 1820
6 FORMAT(/3X,*LTS ROUTINE*)	LTS 1830
RETURN	LTS 1840
END	LTS 1850
	LTS 1860

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SUBROUTINE HTR(F5,T5,P5,X25,F6,T6,P6,X16,X26,X36,FC,TWM,IFP)      HTR   10
*****HTR 20
* HTR 30
*           HTR - CENTRAL RECEIVER (HEATER-REACTOR) ROUTINE      HTR   40
* HTR 50
*****HTR 60
**HIGH TEMP. RECEIVER-REACTOR ROUTINE IS CALLED BY *HTR(F5,T5,P5,X25,F6,*HTR 70
**T6,P6,X16,X26,X36,FC,TWM,IFP) FROM HTS. (5-FOR IP STREAM,6-FOR OUTPUT *HTR 80
**STREAM,FC-FINAL CONVERSION, TWM-MAX.WALL TEMP.,IFP-INDICATOR FOR PRINT)HTR 90
**THE DESIGN IS BASED ON THE BOEING RECEIVER FOR HELIUM (*CLOSED CYCLE *HTR 100
**HIGH TEMP. CENTRAL RECEIVER CONCEPT FOR SOLAR ELECTRIC POWER* EPRI - *HTR 110
**SY 32 INTERIM REPORT,FEB.1976.PREPARED BY BOEING ENG.+CONSTRUCTION CO.*HTR 120
**PROG.MANAGER J.R.GINTZ) *HTR 130
**THE BASIC DESIGN INCLUDES 5600 TUBES 19. METER LONG MADE OF HAYNES 188*HTR 140
**THE PROGRAM ASSUMES ONE SINGLE SOURCE TEMP. SEEN BY ALL TUBES AND IDE-*HTR 150
**NTICAL TEMP.-CONVERSION PROFILE IN ALL TUBES. TUBES ARE ASSUMED TO BE *HTR 160
**COATED BY FE2O3 CATALYST FOR THE DISSOCIATION REACTION OF SO3. MASS TR*HTR 170
**ANSFER COEFF. KG AND HEAT TRANSFER COEFF. H ARE ASSUMED FUNCTIONS OF T,HTR 180
**MASS VELOCITY, AND PRESSURE. CP, DHR (DELTA HEAT OF REACTION), *HTR 190
**AND KP ARE CONSIDERED TO BE FUNCTION OF TEMP.(KP(T) IS TAKEN FROM G. *HTR 200
**NICKLESS *INORGANIC SULPHUR CHEMISTRY* ELSEVIER,1968 P.546 CP(T) AND *HTR 210
**DHR(T) ARE EXTERN,L FUNCTION) *HTR 220
**IT IS ASSUMED THAT THE RECEIVER ABSORBED 230 MWT. T-SOURCE AND THE *HTR 230
**TEMP. PROFILE IN /ND OUTSIDE THE TUBE AS WELL AS THE CONVERSION OF SO3*HTR 240
**ARE DETERMINED BY NEWTON-RAPHSON ITERATION TECHNIQUE TO PROVIDE FOR *HTR 250
**THE ABOVE MENTIONED 230MWT ABSORBED.(SEE PROGRAM FLOWSHEET FOR DETAILS)HTR 260
* HTR 270
*EXTERNAL SUBROUTINES USED=CP,DHR,TRKP *HTR 280
* HTR 290
**NOMENCLATURE= *HTR 300
* HTR 310
* A PARTIAL VALUE OF EXPONENT USED IN DERIVING TB *HTR 320
* C CALCULATED BULK CONVERSION *HTR 330
* D NO.OF MOLES DIFFUSED TO REACTION ZONE *HTR 340
* DEN DENOMINATOR FOR MOLE FRC CALCSC *HTR 350
* DF DIFF. BETWEEN F2 AND F1 - PARTIAL VALUE IN EQUATING HEAT*HTR 360
* DIFF DIFFERENCE BETWEEN HEAT DELIVERED AND CALC. HEAT ABSORPD*HTR 370
* DN D *HTR 380
* DT INCREMENT IN SEARCH FOR SOURCE TEMP. T *HTR 390
* DTW DELTA TW (NR CONVERGING ON TW) *HTR 400
* DX DELTA X (NR CONVERGING ON X) *HTR 410
* DZ DELTA Z *HTR 420
* EXDA EXPONENT OF A *HTR 430
* FC FINAL CONVERSION *HTR 440
* FTW FUNCTION FOR TW (DIFF.IN HEAT GIVEN AND HEAT ABSORBED) *HTR 450
* F1 FUNCTION IN NR SCHEME TO CONVERGE ON TQA *HTR 460
* F2 FUNCTION IN NR SCHEME TO CONVERGE ON TQA *HTR 470
* F5 STREAM INPUT (KMOL/S) *HTR 480
* F6 STREAM OUTPUT(KMOL/S) *HTR 490
* G MASS FLOW PFR UNIT CROSS-SEC.OF TUBE. *HTR 500
* H HEAT TR. COLFF. *HTR 510
* I RUNING INDEX POINTING AT A PARTICULAR SECTION IN TUBE *HTR 520
* IFP INDICATOR FOR PRINTING (1-PRINT,0-DONT) *HTR 530
* J RUNING INDEX IN DO LOOPS 7,27 *HTR 540

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*	J1	INDEX USED IN NR SCHEME TO INDICATE FIRST OR SECOND CALC	*HTR	550
*	K	TUBE METAL CONDUCTIVITY	*HTR	560
*	KG	MASS TR. COEFF.	*HTR	570
*	L	LENGTH OF TUBE (METER)	*HTR	580
*	LON	NO. OF ITERATION IN DO LOOP 5	*HTR	590
*	M	RUNING INDEX IN DO LOOP 20	*HTR	600
*	MU	VISCOSITY OF THE STREAM (CP)	HTR	610
*	N	RUNING INDEX IN DO LOOP -5	*HTR	620
*	NO	NOS+1 INDEX USED TO PREPARE OUTPUT STREAM (LAST SECTION)	*HTR	630
*	NOS	NO. OF SECTIONS IN TUBE	*HTR	640
*	NOT	NUMBER OF TUBES IN THE REACTOR	HTR	650
*	P	TOTAL PRESSURE IN RECEIVER TUBES	*HTR	660
*	PAI	3.14	*HTR	670
*	PP	GAS BULK PRESSURE ARRAY	*HTR	680
*	PS	PARTIAL PRESSURE OF SO2 CONVERTED	*HTR	690
*	P5	INPUT STREAM PRESSURE	*HTR	700
*	P6	OUTPUT STREAM PRESSURE	*HTR	710
*	Q	HEAT DELIVERED FROM RADIATING SOURCE	*HTR	720
*	QR	HEAT ABSORBED BY REACTION	*HTR	730
*	QS	SENSIBLE HEAT ABSORBED BY GAS	*HTR	740
*	REF	REYNOLDS NUMBER FACTOR (DIMENSIONLESS)	HTR	750
*	RFY	CONST. USED IN CALC. OF Y%S (RATIO FOR Y).	*HTR	760
*	RKP	REACTION KP AS FUNCTION OF TS.	*HTR	770
*	SIGMA	STEFAN BOLTZMANN CONST.	*HTR	780
*	STHABG	SUM OF TOTAL HEAT ABSORBED BY GAS	*HTR	790
*	SUA	SURFACE UNIT AREA (PAI*TID*DZ) CONST. USED IN CALC. Q\$S	*HTR	800
*	T	SOURCE TEMP. (RADIATING SOURCE)	*HTR	810
*	TB	BULK GAS TEMP.	*HTR	820
*	THABG	TOTAL HEAT ABSORBED BY GAS	*HTR	830
*	TID	TUBE INSIDE DIAMETER (METER)	*HTR	840
*	TQA	TOTAL Q AVAIL/BLE (MWT)-HEAT ABSORBED BY CENTRAL RECEIVER	*HTR	850
*	TRKPX	KP OF REACTION FOR A PARTICULAR VALUE OF X.	*HTR	860
*	TS	SURFACE TEMP. (INSIDE TUBE WALL TEMP.)	*HTR	870
*	TW	EXTERNAL TUBE WALL TEMP.	*HTR	880
*	TWM	MAX. TUBE WALL TEMP.	*HTR	890
*	TWT	TUBE WALL THICKNESS	*HTR	900
*	T4		*HTR	910
*	T5	TEMP. OF INPUT STREAM	*HTR	920
*	T6	TEMP. OF OUTPUT STREAM	*HTR	930
*	W	TOTAL MASS FLOW (MOLE/SEC)	*HTR	940
*	X	CONVERSION	*HTR	950
*	X1	TEMPORARY VALUE OF X IN NR SCHEME TO FIND IT.	*HTR	960
*	X16	MOLE FR. O2 IN F6	*HTR	970
*	X25	MOLE FR. SO2 IN F5	*HTR	980
*	X26	MOLE FR. SO2 IN F6	*HTR	990
*	X36	MOLE FR. SO3 IN F6	*HTR	1000
*	Y02	MOLE FR. O2 IN BULK	*HTR	1010
*	YS02	MOLE FR. SO2 IN BULK	*HTR	1020
*	YS03	MOLE FR. SO3 IN BULK	*HTR	1030
*	Z	LENGTH OF TUBE AT SECTION BEING CALC.	*HTR	1040
*		*****	*HTR	1050
*			*HTR	1060
*		DIMENSION TW(100),TS(100),TB(100),X(100),YS03(100),YS02(100)	HTR	1070
*		DIMENSION Y02(100),PB(100),PS(100),Q(100),QR(100),QS(100),Z(100)	HTR	1080
*		DIMENSION C(100),F(11)	HTR	1090
*		REAL K,KG,L,TRKP,MU	HTR	1100
*			*HTR	1110

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*PHYSICAL DATA AND CONSTANTS.
  DATA K, L,NOS,TID,TWT,X(1),TW(1),TGA,LON/30.,
  10.037,0.008,0.1,885.,230.,100/
  DATA NOT/5600/
*CONSTANTS AND INITIAL CONDITIONS.
  DATA SIGMA,PAI,YO2(1)/ 4.88E-08,3.141592,0./
*CONSTANTS AND CONVERSION FACTORS
  DZ=L/NOS
  W=F5*3600.
  G=W/NOT/PAI/TID**2*4.
  RFY=4.*DZ/G/1ID
  P=P5
  YSO2(1)=X25
  SUA=PAI*TID*DZ
  TB(1)=T5
  PB(1)=P*YSO2(1)
  YSO3(1)=1.0-YSO2(1)
  T=1200.
  F1=0.
  DO 20 M=1,20
24 T4=T**4
  I=1
  STHABG=0.
  1 DO 5 N=1,LON
  J1=1
*CALCULATE RADIATED HEAT PER UNIT AREA Q
  6 Q(I)=SIGMA*(T4-TW(I)**4)
*CALCULATE INSIDE TUBE WALL TEMPERATURE TS
  TS(I)=TW(I)-Q(I)*TWT/K
*USE FIRST ESTIMATE OF X(I) FROM KNOWN APPROXIMATE FUNCTION OF TS(I).
  IF(TS(I).GT.1120..OR.TS(I)..T.880.) GO TO 79
  IF(I.NE.1) GO TO 79
  X(I)=6.83E-23*TS(I)**7.152
*CALCULATE HEAT ABSORBED BY REACTION PER UNIT AREA GR=DHR*KG*(PS-PB)
*FIND PS FROM X VS TS DEPENDENCY. X IS FOUND BY TRIAL AND ERROR.
*REACTION CONSTANT=RKP
  79 RKP=10.0**(4.765-5022./TS(I))
  DO 7 J=1,10
  X1=X(I)
  TRKPX=TRKP(X1,P,YO2(1),YSO2(1),YSO3(1))
  X1=X(I)+0.005
  DX=.005*(TRKPX-RKP)/(TRKP(X1,P,YO2(1),YSO2(1),YSO3(1))-TRKPX)
  X(I)=X(I)-DX
  IF(X(I).GT.1.) X(I)=.999
  IF(ABS(DX)-0.001)8,8,7
  7 CONTINUE
* EQUILIBRIUM CONVERSION FOR THIS SECTION IS FOUND
*CALCULATE PS OF SC2
  8 PS(I)=2.*P*(YSO2(1)+YSO3(1)*X(I))/(2.+YSO3(1)*X(I))
*CALCULATE HEAT AND MASS TRANSFER COEFFICIENTS FOR THIS SECTION.
  MU=2.46E-3+3.2E-5*TB(I)
  REF=(.822*G/MJ)**.81
  H=REF*MU*.782
  KG=1.50E-6*REF*TB(I)**.81/P5
*CALCULATE DN PER UNIT AREA. DN=KG*(PS-PB)
  D =KG*(PS(I)-PB(I))
*CALCULATE QR

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*HTR 1120
19.,95,*HTR 1130
HTR 1140
HTR 1150
*HTR 1160
HTR 1170
*HTR 1180
HTR 1190
HTR 1200
HTR 1210
HTR 1220
HTR 1230
HTR 1240
HTR 1250
HTR 1260
HTR 1270
HTR 1280
HTR 1290
HTR 1300
HTR 1310
HTR 1320
HTR 1330
HTR 1340
HTR 1350
HTR 1360
*HTR 1370
HTR 1380
*HTR 1390
HTR 1400
HTR 1410
HTR 1420
HTR 1430
HTR 1440
*HTR 1450
*HTR 1460
*HTR 1470
HTR 1480
HTR 1490
HTR 1500
HTR 1510
HTR 1520
HTR 1530
HTR 1540
HTR 1550
HTR 1560
HTR 1570
*HTR 1580
*HTR 1590
HTR 1600
HTR 1610
HTR 1620
HTR 1630
HTR 1640
HTR 1650
*HTR 1660
HTR 1670
*HTR 1680

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QR(I)=DHR(TS(I))*D
*CALCULATE SENSIBLE HEAT PER UNIT AREA QS=H*(TS-TB)
QS(I)=H*(TS(I)-TB(I))
X(I+1)=X(I)
IF(J1.GE.2) GO TO 11
J1=2
I=I+1
DN=D
TW(I)=TW(I-1)+1.
TB(I)=TB(I-1)
PB(I)=PB(I-1)
YO2(I)=YO2(I-1)
YSO2(I)=YSO2(I-1)
YSO3(I)=YSO3(I-1)
GO TO 6
11 I=I-1
FTW=Q(I)-QR(I)-QS(I)
DTW=FTW/(Q(I+1)-QR(I+1)-QS(I+1)-FTW)
TW(I)=TW(I)-DTW
IF(ABS(DTW)-0.01)9,9,5
5 CONTINUE
*IF LOOP COMPLETED NO CONVERGENCE ON TW IN LONG STEPS.
PRINT 2,I,T,TW(I),TS(I)
PRINT 3,Q(I),QR(I),QS(I)
PRINT 4
2 FORMAT(/* DIDNT CONVERGE ON TW. I=*,I4,2X,*T,TW,TS=*,3(F6.1,2X),*
1 RESPECTIVELY.
3 FORMAT(/2X,*Q,QR,QS,THABG=*,4(E11.4,2X),*RESPECTIVELY*)
4 FORMAT(/2X,*HOWEVER ASSUMED TW IS OK PROGRAM CONTINUE*)
*CALCULATE TOTAL HEAT ABSORBED BY GAS - THABG
9 THABG=QR(I)+QS(I)
*ACCUMULATE HEAT ABSORBED BY GAS - STHABG
STHABG=STHABG+THABG*SUA
* EVALUATE TB-H*(TS-TB)*PAI*TID*DZ=G*PAI*TID**2/4*CP*DTB
* AFTER INTEGRATION THE ABOVE EQ. RESULTS IN THE FOLLOWING
A=4.*H*DZ/(G*TID)
EXPA=EXP(-A/CP(TB(I),YO2(I),YSO2(I),YSO3(I)))
TB(I+1)=TS(I)-(TS(I)-TB(I))*EXPA
*CALCULATE GAS BULK COMPOSITION
DEN=1.+DN*RFY/2.
YSO3(I+1)=(YSO3(I)-DN*RFY)/DEN
YSO2(I+1)=(YSO2(I)+DN*RFY)/DEN
YO2(I+1)=1.-YSO2(I+1)-YSO3(I+1)
*UPDATE Z,TW,PB
Z(I)=I*DZ
PB(I+1)=YSO2(I+1)*P
* CALCULATE BULK CONVERSION - C
C(I)=(1.-YSO3(I)/YSO3(1))/(1.+YSO3(I)/2.)
*UPDATE FOR NEXT SECTION AFTER CHECKING FOR COMPLETION. IF DONE-PRINT
IF(NOS-I)26,26,25
25 I=I+1
GO TO 1
*ALL CALCULATIONS ARE COMPLETED. PRINT RESULTS.
*CHANGE Q INTO ACCUMULATIVE POWER ABSORBED
26 Q(1)=Q(1)*SUA
QR(1)=QR(1)*SUA
QS(1)=QS(1)*SUA

```

```

HTR 1690
*HTR 1700
HTR 1710
HTR 1720
HTR 1730
HTR 1740
HTR 1750
HTR 1760
HTR 1770
HTR 1780
HTR 1790
HTR 1800
HTR 1810
HTR 1820
HTR 1830
HTR 1840
HTR 1850
HTR 1860
HTR 1870
HTR 1880
HTR 1890
*HTR 1900
HTR 1910
HTR 1920
HTR 1930
*HTR 1940
HTR 1950
HTR 1960
HTR 1970
*HTR 1980
HTR 1990
*HTR 2000
HTR 2010
*HTR 2020
*HTR 2030
HTR 2040
HTR 2050
HTR 2060
*HTR 2070
HTR 2080
HTR 2090
HTR 2100
HTR 2110
*HTR 2120
HTR 2130
HTR 2140
*HTR 2150
HTR 2160
*HTR 2170
HTR 2180
HTR 2190
HTR 2200
*HTR 2210
*HTR 2220
HTR 2230
HTR 2240
HTR 2250

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```

DO 27 J=2,NOS
Q(J)=Q(J)*SUA+Q(J-1)
QR(J)=QR(J)*SUA+QR(J-1)
QS(J)=QS(J)*SUA+QS(J-1)
27 CONTINUE
STHABG=NOT*1.1E-6*STHABG
DIFF=NOT*1.1E-6*Q(NOS)-STHABG
*CHECK FOR DIFFERENCE BETWEEN AVAILABLE Q (TQA) AND CALC. Q.
*CHANGE SOURCE TEMP (T) ACCORDINGLY.
IF(F1)12,13,12
13 F1=STHABG-TQA
T=T+2.
GO TO 24
12 F2=STHABG-TQA
DF=(F2-F1)/2.
DT=F2/DF
IF(F1*F2.LT.0. .AND. DF.LT.0.) DT=-DT
T=T-DT
F1=F2
IF(ABS(F2)-1.01)10,10,20
20 CONTINUE
PRINT 80
80 FORMAT(/3X,*NO CONVEGENCE ON TQA*)
*ZERO IRRELEVANT VARIABLES AT THE TUBE END
10 PS(I+1)=0.
TS(I+1)=0.
TW(I+1)=0.
Z(I+1)=Z(I)
Q(I+1)=0.
QR(I+1)=0.
QS(I+1)=0.
X(I+1)=X(I)
C(I+1)=C(I)
NO=NOS+1
*SUPPRESS TABLE PRINTING IF IFP=0.
IF(IFP.EQ.0) 30 TO 18
PRINT 30
30 FORMAT(/10X,*HIGH TEMP REACTOR DESIGN-COMPUTATION RESULTS*/)
PRINT 31
31 FORMAT(/8X,3HNOS,8X,1HL,9X,2HTW,9X,2HTS,9X,2HTB,8X,1HQ,9X,2HQR,
1 9X,2HQS,12X,1HC,8X,5HY-SO3,6X,5HY-SO2,7X,4HY-O2/)
OPRINT 32,(J,Z(J),TW(J),TS(J),TB(J),Q(J),QR(J),QS(J),C(J),YSO3(J),
1YSO2(J),YO2(J),J=1,NO)
PRINT 33,STHABG,T,DIFF
32 FORMAT(/I11,F11.2,3F11.1,3E11.4,4F11.3)
33UFORMAT(/10X,*THERMAL POWER ABSORBED BY GAS-*,E11.4,*MW-THERMAL)
1 SOURCE TEMP. =*,F5.1,3H(K),2X,5HDIFF=,E10.4,2HMMW)
PRINT 15,(Z(J),X(J),J=1,NO)
15 FORMAT(/3X,F5.2,F11.4)
*SET OUTPUT VARIABLES FOR CALLING PROGRAM
18 P6=P
FC=C(NOS)
F6=F5*(1.+(1.-X25)*FC/2.)
T6=TB(NO)
X16=Y02(NOS)
X26=YSO2(NOS)
X36=YSO3(NOS)
HTR 2260
HTR 2270
HTR 2280
HTR 2290
HTR 2300
HTR 2310
HTR 2320
HTR 2330
HTR 2340
HTR 2350
HTR 2360
HTR 2370
HTR 2380
HTR 2390
HTR 2400
HTR 2410
HTR 2420
HTR 2430
HTR 2440
HTR 2450
HTR 2460
HTR 2470
HTR 2480
HTR 2490
HTR 2500
HTR 2510
HTR 2520
HTR 2530
HTR 2540
HTR 2550
HTR 2560
HTR 2570
HTR 2580
HTR 2590
HTR 2600
HTR 2610
HTR 2620
HTR 2630
HTR 2640
HTR 2650
HTR 2660
HTR 2670
HTR 2680
HTR 2690
HTR 2700
HTR 2710
HTR 2720
HTR 2730
HTR 2740
HTR 2750
HTR 2760
HTR 2770
HTR 2780
HTR 2790
HTR 2800
HTR 2810
HTR 2820

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```
TWM=TW(NOS)
IF(IFP.EQ.0)GO TO 14
PRINT 22,F6,I6,P6,X16,X26,X36,FC,TWM
22 FORMAT(/3X,*HTR RETURNS WITH= F(6) T(6) P(6)
1 X1(6) X2(6) X3(6) FC TWM*/20X,8F11.3)
14 RETURN
END
```

HTR 2830  
HTR 2840  
HTR 2850  
HTR 2860  
HTR 2870  
HTR 2880  
HTR 2890



```

SUBROUTINE LTR(FC,QAAN,IN,J,K)
*****
* JUNE 1,1978
* LTR - LOW TEMP. REACTOR
*
*****
*CALCULATIONS ARE FOR ADIABATIC OXIDATION OF SO2 TO SO3 IN A REACTOR
*WICH REACHES EQUILIBRIUM CONVERSION.I.E. RESULTS OF FC AND TEQ ARE
*GIVEN FOR DATA FULFILING THE REACTION CONSTANT,KP,EQUATION (REF. -
*NICLESS).
*****
COMMON/STREAM/F(60),P(60),T(60),H(60),X1(60),X2(60),X3(60)
DIMENSION X(5),DX(5),TEQ(5),HR(5),HL(5)
DATA EPSDT,DDX/1.01,0.001/
DATA RIGT/693./
JI1=IN
IF(X1(IN)-X2(IN)/2.)13,13,14
13 XM=2.*X1(IN)/X2(IN)-0.011
GO TO 3
14 XM=0.989
23 DO 24 I=1,5
FACTOR=0.15*I
X(I)=FACTOR*XM
24 TEQ(I)=1000.-100.*I
DHR420=DHR(T(IN))
I=1
P(J)=P(IN)
P(K)=P(IN)
IF(X1(JI1))19,19,20
20 IF(X2(JI1))19,19,21
19 PRINT 22,X1(JI1),X2(JI1),X3(JI1),JI1
22 FORMAT(3X,*NO MORE REACTANTS. X1=*,F5.3,3X,3HX2=,F5.3,3X,3HX3=,F5.
13,3X,2HJ=,I2,*LTR*)
X(I)=0.
CALL RECOPY(JI1,J)
GO TO 4
21 CONTINUE
DO 26 I=1,5
DO 7 N=1,20
L=1
16 RKP=10.**(5022./TEQ(I)-1.765)
DO 8 M=1,10
XT=X(I)
TRKPX=TKP(XT,P(J),X1(JI1),X2(JI1),X3(JI1))
XT=X(I)+.01
TRKPY=TKP(XT,P(J),X1(JI1),X2(JI1),X3(JI1))
DEN=TRKPY-TRKFX
IF(DEN.EQ.0.) GO TO 26
DXT=0.01*(TRKPX-RKP)/DEN
X(I)=X(I)-DXT
IF(ABS(DXT)-DDX)9,9,5
9 IFPNCM=0

```

GO TO 11	LTR 530
5 IF(X(I).LE.0.) X(I)=0.1*XT	LTR 540
IF(X(I)-XM)8,6,6	LTR 550
6 X(I)=(XT-0.01+XM)/2.	LTR 560
8 CONTINUE	LTR 570
*NO CONVERGENCE MASSEGE	*LTR 580
IFPNCM=1	LTR 590
11 IF(X(I).GT.0.) GO TO J	LTR 600
IF(I.LT.5) GO TO 26	LTR 610
X(I)=0.	LTR 620
GO TO 2	LTR 630
2 IF(X(I)-XM)7,2,1	LTR 640
1 IF(I.LT.5)GO TO 26	LTR 650
X(I)=XM	LTR 660
PRINT 10	LTR 670
10 FORMAT(3X,*100 P.C. CONVERSION IN LTR*)	LTR 680
2 DX(I)=X(I)	LTR 690
HR(I)=(DHR420+DHR(TEQ(I)))/2.	LTR 700
D=1.-X2(IN)*X(I)/2.	LTR 710
F(J)=F(IN)*D	LTR 720
X1(J)=(X1(IN)-X2(IN)*X(I)/2.)/D	LTR 730
X2(J)=X2(IN)*(1.-X(I))/D	LTR 740
X3(J)=1.-X1(J)-X2(J)	LTR 750
H(J)=(4.2*DX(I)*X2(JI1)*HR(I)+H(JI1))*F(JI1)/F(J)	LTR 760
T(J)=TEQ(I)	LTR 770
CALL FINDT(2,J)	LTR 780
IF(L.EQ.2) GO TO 15	LTR 790
FDT1=T(J)-TEQ(I)	LTR 800
L=2	LTR 810
TEQ(I)=TEQ(I)+1.	LTR 820
GO TO 16	LTR 830
15 FDT2=T(J)-TEQ(I)	LTR 840
DT=FDT2/(FDT2-FDT1)	LTR 850
TEQ(I)=TEQ(I)-DT	LTR 860
IF(ABS(DT)-EPSDT)4,4,7	LTR 870
7 CONTINUE	LTR 880
PRINT 28,TEQ(I),DT,RKP,TRKPX,T(J),I	LTR 890
28 FORMAT(3X,*DIDNT CONVERGE ON TEQ. TEQ=*,F6.1,3X,3HDT=*,F6.1,3X,4HRK	LTR 900
1P=*,E12.4,3X,4HTRK=*,E12.4,3X,*T(J)=*,F6.1,*LTR I=*,I2)	LTR 910
26 CONTINUE	LTR 920
PRINT 29,J,F(J),P(J),T(J),H(J),X1(J),X2(J),X3(J)	LTR 930
29 FORMAT(3X,*STREAM I=*,I2,7E12.4,*COPY IN INTO J*)	LTR 940
CALL RECOPY(IN,J)	LTR 950
4 CALL RECOPY(J,K)	LTR 960
T(K)=RIGT	LTR 970
CALL ENTR2(T(K),X2(K),X3(K),H(K))	LTR 980
HL(I)=F(J)*(H(J)-H(K))	LTR 990
QAAN=HL(I)	LTR 1000
FC=X(I)	LTR 1010
IF(IFPNCM.EQ.0) GO TO 12	LTR 1020
PRINT 17,X(I),DXT,TEQ(I),T(J),IN	LTR 1030
17 FORMAT(/3X,*NO CONVERGE ICE ON X=*,E10.4,3X,*DXT=*,E10.4,3X,*TEQ=*,	LTR 1040
1E10.4,*T(J)=*,F6.1,3X,*INPUT STREAM TO LTR IS *,I2)	LTR 1050
PRINT 30,I,N,TEQ(I),RKP,X(I),TRKPX,TRKPY,DEN,DXT	LTR 1060
30 FORMAT(3X,* N TEQ R&P X TRKPX TRKPY DEN DXT*,/3X,2I5,7E10	LTR 1070
1.4)	LTR 1080
12 RETURN	LTR 1090
END	LTR 1100

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SUBROUTINE DIST(F,TF,PF,HF,XF,QR,XD,P,PRS02,N,D,TM, PD,HLM, YM, DIST 10
1 B,TB,PB,HB,XB,IFP) DIST 20
*****DIST 30
*
*
*   UPDATED 8/15/78
*   DISTILLATION COLUMN ROUTINE
*
*****DIST 80
*
*INPUTS TO THE PROGRAM ARE=
* FEED= FLOW-F, SO2 MOLE FRAC.-XF, ENTHALPY-HF, PRESSURE-PF, TEMP-TFDIST 110
* TOP= SO2 MOLE FRAC.-XD, PERCENT RECOVERY OF SO2-PRS02 DIST 120
* BOTTOM= REBOILER DUTY-QR DIST 130
* GENERAL= TOTAL PRESSURE-P, MAX.NO.OF PLATES PERMITTED-N DIST 140
*
*OUTPUT= THE PROGRAM CALC. OVERALL MATERIAL AND ENERGY BALANCES FOR A DIST 160
* BINARY DISTILLATION COLUMN SEPARATING SO2 FROM SO3 DIST 170
*
* INPUT DATA= FEED= F,TF,PF,HF,XF. BOTTOM= QR. TOP= XD. GENERAL=P,PRS02DIST 190
*,N
*FOREACH PLATE=L=LIQUID,V=VAPOR,X=SO2 MOLE FRAC.IN LIQ,Y=SO2 MOLE FRAC. DIST 210
*IN VAP.,T=PLATE TEMP.,HL=LIQ.ENTHALPY,HV=VAP.ENTHALPY. DIST 220
*ALL UNITS CONSIDERED TO BE IN METRIC,I.E. F-MOLE/HR.,T-K,P-BAR,H-KJ/KMOLDIST 230
*Q-MW(CONVERTED INTO KJ/HR IN THE TEXT) ) DIST 240
*ROUTINE ACCEPT FLOWS IN KMOL/SEC AND RETURNS THEM IN THE SAME UNITS DIST 250
*BUT CALC. ARE MADE IN KMOL/HR. NECESSARY CONVERSIONS ARE MADE BEFORE DIST 260
*AND AFTER THE CALCS. DIST 270
*
*
* NOMENCLATURE=
*
* A JACOBIAN MATRIX COMPONENT IN NR FOR X AND L DIST 300
* A11 INVERSE JACOBIAN COMPONENT IN NR FOR X AND L DIST 310
* A12 INVERSE JACOBIAN COMPONENT IN NR FOR X AND L DIST 320
* A21 INVERSE JACOBIAN COMPONENT IN NR FOR X AND L DIST 330
* A22 INVERSE JACOBIAN COMPONENT IN NR FOR X AND L DIST 340
* B BOTTOM LIQUID OUTPUT FLOW (KMOL/HR) DIST 350
* C JACOBIAN MATRIX COMPONENT IN NR FOR X AND L DIST 360
* D DISTILLATE FLOW (KMOL/SEC) -OUTPUT DIST 370
* DENFR2 DENOMINATOR FOR FR2 -NR FLASH CALCS. DIST 380
* DENFR3 DENOMINATOR FOR FR3 -NR FLASH CALCS. DIST 390
* DET DETERMINANT OF JACOBIAN MATRIX IN NR FOR X AND L DIST 400
* DFR DIFF. IN NR FLASH CALCS. DIST 410
* DH DIFF. BETWEEN GIVEN AND CALC. FEED ENTHALPIES (ARRAY) DIST 420
* DHDX DERIVATIVE OF H W.R.T. X - NR CALCS. FOR X AND L DIST 430
* DHF TOLERANCE VALUE FOR DH -ACCEPTABLE CALC. H OF FLASH DIST 440
* DL INCREMENT OF L IN NR FOR X AND L DIST 450
* DR INCREMENT OF R IN NR FLASH CALCS. DIST 460
* DSOY DIFF. BETWEEN 1. AND SUM OF Y'S AT B FOR ADJUSTMENT CALC DIST 470
* DV DEVIATION OF V AT TOP FROM OVERALL MATERIAL BAL. CALCS. DIST 480
* DX DELTA X FOR CALC. DH/DX DIST 490
* DXJ INCREMENT OF X IN NR FOR X AND L DIST 500
* DY DIFF. BETWEEN CALC. COMPOSITION AND GIVEN COMP. AT D DIST 510
* E JACOBIAN MATRIX COMPONENT IN NR FOR X AND L DIST 520
* EDR MAX. TOLERANCE FOR DR IN NR FLASH CALCS. DIST 530
* F FEED FLOW (KMOL/SEC) DIST 540

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*	FL	LIQUID IN FLASHED FEED	*DIST 550
*	FR	NR FUNCTION IN FLASH CALC.	*DIST 560
*	FR2	PARTIAL NR FUNCTION IN FLASH CALCS.	*DIST 570
*	FR3	PARTIAL NR FUNCTION IN FLASH CALCS.	*DIST 580
*	FV	VAPOR IN FLASHED FEED	*DIST 590
*	F1	NR FUNCTION IN L AND X CALCS.	*DIST 600
*	F2	NR FUNCTION IN L AND X CALCS.	*DIST 610
*	G	JACOBIAN MATRIX COMPONENT IN NR FOR X AND L	*DIST 620
*	HB	ENTHALPY OF BOTTOM STREAM (KJ/KMOL) - OUTPUT	*DIST 630
*	HD	ENTHALPY OF TOP STREAM (KJ/KMOL)	*DIST 640
*	HF	FEED ENTHALPY (KJ/KMOL) - GIVEN	*DIST 650
*	HFC	CALCULATED FEED ENTHALPY	*DIST 660
*	HFF	HEAT IN FEED (HF*F)(KJ/HR)	*DIST 670
*	HFL	ENTHALPY OF LIQUID PORTION IN FLASHED FEED	*DIST 680
*	HFV	ENTHALPY OF VAPOR PORTION IN FLASHED FEED	*DIST 690
*	HL	LIQUID ENTHALPY ARRAY FOR COL. LIQ. STREAMS	*DIST 700
*	HLM	DISTILLATE (CONDENSATE) ENTHALPY(KJ/KMOL) - OUTPUT	*DIST 710
*	HM1P	ENTHALPY CORRESPONDS TO XM1P (NR)	*DIST 720
*	HP1P	ENTHALPY CORRESPONDS TO XP1P (NR)	*DIST 730
*	HV	VAPOR ENTHALPY ARRAY FOR COL. VAPOR STREAMS	*DIST 740
*	I	INDEX OF DO LOOP USING NR TO FIND L AND X2	*DIST 750
*	IFP	INDICATOR FOR PRINTING	*DIST 760
*	J	DO LOOP 50 INDEX -FLASH CALC.+DO LOOP 60 INDEX-PLATES	*DIST 770
*	JR	DO LOOP 51 INDEX - NR IN FLASH CALC.	*DIST 780
*	KB2	VOLATILITY CONST. FOR SO2 IN B	*DIST 790
*	KB3	VOLATILITY CONST. FOR SO3 IN B	*DIST 800
*	KS02	VOLATILITY CONST. FOR SO2 - FLASH AND PLATE TO PLAT CALC	*DIST 810
*	KS03	VOLATILITY CONST. FOR SO3 - FLASH AND PLATE TO PLAT CALC	*DIST 820
*	L	LIQUID FLOW ARRAY FOR COL. PLATES (KMOL/HR)	*DIST 830
*	LHB	LATENT HEAT OF B	*DIST 840
*	M	J+1	*DIST 850
*	N	NO. OF PLATES	*DIST 860
*	NFP	FEED PLATE NO. - INDICATOR IN SEARCH FOR FEED PLATE	*DIST 870
*	P	DISTILLATION COLUMN PRESSURE (BAR) -PRESCRIBED	*DIST 880
*	PB	BOTTOM STREAM PRESSURE (BAR) -OUTPUT	*DIST 890
*	PD	DISTILLATE STREAM PRESSURE (BAR) -OUTPUT	*DIST 900
*	PF	FEED PRESSURE (IP) (BAR) - BEFORE FLASH	*DIST 910
*	PRS02	PERCENT RECOVERY OF SO2	*DIST 920
*	QC	CONDENSER HEAT LOAD (KJ/SEC)	*DIST 930
*	QR	REBOILER HEAT LOAD (KJ/SEC)	*DIST 940
*	QRM	MIN. REQUIRED REBOILER DUTY	*DIST 950
*	R	THE RATIO FV/F IN FLASH CALCS.	*DIST 960
*	RS	(L/V)MIN FOR STRIPPING SECTION	*DIST 970
*	SL	INTERMEDIATE VALUE OF LIQUID FLOW AT FEED PLATE	*DIST 980
*	SV	INTERMEDIATE VALUE OF VAPOR FLOW AT FEED PLATE	*DIST 990
*	SXFM1	SUM OF X'S MINUS 1	*DIST1000
*	SYFM1	SUM OF Y'S MINUS 1	*DIST1010
*	T	TEMP. ARRAY FOR PLATES STREAMS(K)	*DIST1020
*	TB	TEMP. OF BOTTOM STREAM(K) - OUTPUT	*DIST1030
*	TD	TEMP. OF TOP D STREAM(K) - OUTPUT	*DIST1040
*	TF	FEED TEMP. (K) -GIVEN AS IP	*DIST1050
*	TFF	FLASH TEMP. OF FEED(K)	*DIST1060
*	TF1	VALUE OF TEMP. OF FLASH (INTERMEDIATE RESULT NR METHOD)	*DIST1070
*	TF2	VALUE OF TEMP. OF FLASH (INTERMEDIATE RESULT NR METHOD)	*DIST1080
*	TM	DISTILLATE TEMP. (K) - OUTPUT	*DIST1090
*	TM1P	TEMP. CORRESPONDS TO XM1P (NR X,L)	*DIST1100
*	TP1P	TEMP. CORRESPONDS TO XP1P (NR X,L)	*DIST1110

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*      V      VAPOR FLOW ARRAY FOR COL. PLATES (KMOL/HR)      *DIST1120
*      VB     VAPOR FLOW FROM REBOILER                        *DIST1130
*      VMIN   REQUIRED MIN. VAPOR FLOW FROM REBOILER          *DIST1140
*      X      LIQUID SO2 COMPOSITION ARRAY FOR COL. PLATES (MOL.FR.) *DIST1150
*      XB     COMPOSITION (SO2 MOL.FR.) OF BOTTOM STREAM      *DIST1160
*      XD     COMPOSITION (SO2 MOL.FR.) OF TOP STREAM -PRESCRIBED. *DIST1170
*      XF     SO2 COMPOSITION IN FEED - GIVEN IP. (MOL.FR.)  *DIST1180
*      XF2    MOLE FR. OF SO2 IN LIQUID PORTION OF FLASHED FEED *DIST1190
*      XF3    MOLE FR. OF SO3 IN LIQUID PORTION OF FLASHED FEED *DIST1200
*      XM1P   X(M)-0.01 PERTURBED VALUE IN NR FOR X AND L    *DIST1210
*      XP1P   X(M)+0.01 PERTURBED VALUE IN NR FOR X AND L    *DIST1220
*      Y      VAPOR COMPOSITION (SO2 MOL.FR.) ARRAY FOR COL. PLATES *DIST1230
*      YB2    VAPOR COMPOSITION (SO2 MOL.FR.) IN B           *DIST1240
*      YB3    VAPOR COMPOSITION (SO3 MOL.FR.) IN B           *DIST1250
*      YM     DISTILLATE COMPOSITION (SO2 MOL.FR.) -OUTPUT   *DIST1260
*      Y2     MOLE FR. OF SO2 IN VAPOR PORTION OF FLASHED FEED *DIST1270
*      Y3     MOLE FR. OF SO3 IN VAPOR PORTION OF FLASHED FEED *DIST1280
*****DIST1290
*
      DIMENSION DH(21)
      REAL L( 50),V( 50),X( 50),Y( 50),T( 50),HL( 50),HV( 50)
      REAL KB2,KB3,KS02,YS03,LHB
      DATA EDR, DHF/0.001,100./
*PRINT INPUT FOR RECORDING AND CHECKING
      PRINT 69
      69 FORMAT(/4X,*DISTILLATION COLUMN*)
      IF(IFP.EQ.0)GO TO 5
      PRINT 82,F,TF,PF,HF,XF,QR,XD,P,PRS02,N
      820FORMAT(1X,* INPUT DATA*/1X,*STRFAM      *,4X,1HF,9X,1HT,9X,1HP,9X,1HDIST1400
      1H,9X,1HC,9X,1HQ/,* FEED      *,5F10.3/,* BOTTOM      *,50X,F10.3/,* DIDIST1410
      2STILATE*,40X,F10.3/,2X,2HP=,F5.2,3X,6HPRS02=,F5.3,3X,2HN=,I3/) DIST1420
      PRINT 14
      14 FORMAT(/3X,*RESULTS OF THE DISTILLATION COLUMN*)
      DIST1440
*FIRST,          CONVERT Q TO KJ/HR
      5 QR=QR*3.6E3
      DIST1460
*CONVERT FLOW INTO MOLE/HR
      F=F*3600.
      DIST1480
*SECOND,CALCULATE OVERALL MATERIAL AND ENRGY BALANCES ON ALL 3-STREAMS*DIST1490
      D=F*XF*PRS02/XD
      DIST1500
      B=F-D
      DIST1510
      XB=(F*XF-D*XD)/B
      DIST1520
*CALC. T&S AND H&S OF B AND D
      CALL BPTR(P,XD,TD)
      DIST1540
      CALL BPTR(P,XB,TB)
      DIST1550
      CALL ENTRI(TD,XD,HD)
      DIST1560
      CALL ENTRI(TB,XB,HB)
      DIST1570
*FLASH CALCS. FOR THE FEED STREAM (TFF= FLASH FEED TEMP)
      *DIST1580
*IF PF SMALLER OR EQ. TO THE DIST. COL. PRESSURE THERE IS NO FLASH
      *DIST1590
*SEPARATION AND FEED IS ASSUMED TO BE AT COL. PRESS. AND AT LIQ. STATE
      *DIST1600
      IF(PF-P.LE.0.) GO TO 13
      DIST1610
*FIRST GUESSES OF TFF-ASSUME TFF=T(BP)+1.
      *DIST1620
      CALL BPTR(P,XF,TFF)
      DIST1630
      TFF=TFF+1.
      DIST1640
      HFF=HF*F
      DIST1650
*FLASH CALC. ARE ACCORDING TO C.D.HOLLAND - FUND.AND MODELING OF SEPARATDIST1660
*PROCESSES 1975,PP. 59-67
      *DIST1670
      1 DO 50 J=1,20
      DIST1680

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R=0.5
*FIND KSO2 AND KSO3 BY THE VOLATILITY K CONST. ROUTINE - VKCR          DIST1690
CALL VKCR(P,TFF,KSO2,KSO3)                                           *DIST1700
*CHECK IF B.P.'TFF'D.P. NOTE THAT IF TFF IS NOT WITHIN THESE BOUNDARIES *DIST1710
*CORRECTION IS MADE AND LOOP STARTS FROM FRESH                        *DIST1720
SXF1=KSO2*XF+KSO3*(1.-XF)-1.                                         *DIST1730
SYF1=XF/KSO2+(1.-XF)/KSO3-1.                                         DIST1740
IF(SXF1.GT.0.0) GO TO 2                                               DIST1750
8 TFF=TFF+1.                                                           DIST1760
GO TO 1                                                                DIST1770
2 IF(SYF1.GT.0.0) GO TO 3                                             DIST1780
7 TFF=TFF-1.                                                           DIST1790
GO TO 1                                                                DIST1800
*SEARCH FOR R=FV/F START HERE USING NEWTON RAPHSON METHOD.          *DIST1810
3 DO 51 JR=1,10                                                       *DIST1820
DENFR2=1.-R*(1.-KSO2)                                               DIST1830
DENFR3=1.-R*(1.-KSO3)                                               DIST1840
FR2=XF/DENFR2                                                         DIST1850
FR3=(1.-XF)/DENFR3                                                  DIST1860
FR=FR2+FR3-1.                                                         DIST1870
DR=FR2*(1.-KSO2)/DENFR2+FR3*(1.-KSO3)/DENFR3                      DIST1880
R=R-DR                                                                DIST1890
IF(R.LE.0.) GO TO 8                                                  DIST1900
IF(R-1.0.GE.0.0) GO TO 7                                           DIST1910
IF(ABS(DR)-EDR)4,4,51                                               DIST1920
51 CONTINUE                                                           DIST1930
PRINT 76,R,DR                                                         DIST1940
76 FORMAT(3X,*NO CONVERGENCE ON R=FV/F DIST. COL. R,DR=*,2E10.4)    DIST1950
*ASSUME CONVERSION ON R. CALC. AND CHECK ENERGY BAL. FOR THE FLASH CALC. DIST1960
4 FV=R*F                                                               DIST1970
FL=F-FV                                                                DIST1980
XF2=XF/(R*(KSO2-1.)+1.)                                           DIST1990
XF3=1.-XF2                                                           DIST2000
*CALC. Y2 AND Y3                                                    DIST2010
Y2=KSO2*XF2                                                         DIST2020
Y3=1.-Y2                                                             DIST2030
CALL ENTR1(TFF,XF2,HFL)                                             DIST2040
CALL ENTR2(TFF,Y2,Y3,HFV)                                           DIST2050
HFC=HFL*FL+HFV*FV                                                  DIST2060
DH(J)=HFC-HFF                                                        DIST2070
IF(ABS(DH(J))-DHF)56,56,52                                          DIST2080
52 IF(J.GT.1) GO TO 5?                                              DIST2090
TF1=TFF                                                               DIST2100
IF(DH(J))54,56,55                                                  DIST2110
54 TFF=TFF+1.                                                       DIST2120
GO TO 50                                                             DIST2130
55 TFF=TFF-1.                                                       DIST2140
GO TO 50                                                             DIST2150
53 TF2=TFF                                                           DIST2160
TFF=(TF2*DH(J-1)-TF1*DH(J))/(DH(J-1)-DH(J))                      DIST2170
TF1=TF2                                                               DIST2180
50 CONTINUE                                                           DIST2190
PRINT 500                                                            DIST2200
PRINT 510,TFF,HF,HFC,FL,FV,XF2,XF3,Y2,Y3                          DIST2210
500 FORMAT(/3X,*FLASH CALCS. DIDNT CONVERGE IN 100 STEPS*)        DIST2220
5100FORMAT(/3X,4HTFF=,F5.1,2Y,3HHF=,E11.4,2X,4HHFC=,E11.4,2X,3HFL=,2X,DIST2230
DIST2240
DIST2250

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1E11.4,2X,3HFV=,E11.4,2X,4HXF2=,F5.3,2X,4HXF3=,F5.3,2X,3HY2=,F5.3,2D DIST2260
2X,3HY3=,F5.3) DIST2270
GO TO 1000 DIST2280
*CONTINUE HERE IF NO FLASH CALC. ARE NEEDED. *DIST2290
13 TFF=TF DIST2300
FL=F DIST2310
XF2=XF DIST2320
XF3=1.-XF DIST2330
HFL=HF DIST2340
FV=0. DIST2350
Y2=0. DIST2360
Y3=0. DIST2370
HFV=0. DIST2380
56 IF(IFP.EQ.0)GO TO 6 DIST2390
PRINT 12,TFF,FL,XF2,FV,Y2 DIST2400
12 FORMAT(/3X,*FLASH RESULTS= TFF=*,F7.2,3X,3HFL=,E11.4,3X,4HF2=, DIST2410
1F6.4,3X,3HFV=,E11.4,3X,4HFY2=,F6.4) DIST2420
*REBOILER CALCS. FIRST,FIND BOILER VAPOR COMPOSITION *DIST2430
6 CALL VKCR(P,TB,KB2,KB3) DIST2440
YB2=KB2*XB DIST2450
YB3=KB3*(1.-XB) DIST2460
*ADJUST TO GET YB2+YB3=1. *DIST2470
DSOY=1.-YB2-YB3 DIST2480
YB2=YB2+0.01*DSOY DIST2490
YB3=YB3+0.99*DSOY DIST2500
*CALL LATENT HEAT ROUTINE - LHR. 2-FCR S02,3 FOR S03 *DIST2510
CALL LHR(TB,XB,LHB) DIST2520
VB=QR/LHB DIST2530
*CHECK IF REBOILER HEAT IS SUFFICIENT. IF NOT CALC. FOR MIN QR. *DIST2540
*RS=(L/V)MIN FOR THE STRIPPING SECTION. THIS SLOP IS THE SLOP OF THE LINEDIST2550
* CONNECTING (XB,XB) AND (XF2,Y2). (V)MIN IS THEN FOUND AND COMPARED *DIST2560
*WITH VB. IF VB'(V)MIN, QR IS NOT ENOUGH. (QR)MIN=(V)MIN*LHB. *DIST2570
RS=(Y2-XB)/(XF2-XB) DIST2580
VMIN=B/(RS-1.) DIST2590
IF(VB-VMIN)30,31,9 DIST2600
30 QRM=VMIN*LHB/3.6E6 DIST2610
IF(IFP.EQ.0)GO TO 9 DIST2620
PRINT 32,QRM DIST2630
32 FORMAT(/3X,*HEAT INPUT TO REBOILER IS NOT ENOUGH. QR-MIN SHOULD DIST2640
1BE OVER*,2X,E11.4,2X,2HMW/3X,*DIST. COL. IS CALCUL. FOR QR-MIN*) DIST2650
9 QR=VMIN*LHB DIST2660
VB=VMIN DIST2670
*MAKE REBOILER TO BE PLATE NO. 1 *DIST2680
31 L(1)=B DIST2690
V(1)=VB DIST2700
T(1)=TB DIST2710
Y(1)=YB2 DIST2720
X(1)=XB DIST2730
HL(1)=HB DIST2740
HV(1)=HL(1)+LHB DIST2750
*CALC. DATA FOR PLATE NO.2 *DIST2760
L(2)=VB+B DIST2770
X(2)=(B*XB+VB*YB2)/L(2) DIST2780
CALL BPTR(P,X(2),T(2)) DIST2790
CALL VKCR(P,T(2),KCO2,KSO3) DIST2800
Y(2)=KSO2*X(2) DIST2810
Y3=1.-Y(2) DIST2820

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CALL ENTR1(T(2),X(2),HL(2))
CALL ENTR2(T(2),Y(2),Y3,HV(2))
*PLATE TO PLATE CALCS. ASSUME V(J)=V(J-1),CALC. L(J+1),X(J+1),T(J+1).
V(2)=V(1)
*INITIALIZE FOR FEED PLATE SEARCH
NFP=0
*
DO 60 J=2,N
M=J+1
*FIND L(J+1) FROM OVERALL MATERIAL BALANCE
L(J+1)=L(J)+V(J)-V(J-1)
*FIND X(J+1) FROM SO2 BALANCE
X(J+1)=(L(J)*X(J)+V(J)*Y(J)-V(J-1)*Y(J-1))/L(J+1)
IF(X(J+1).GT.1.0)X(J+1)=1.0
*FIND BUBBLE PT. OF PLATE (J+1)
DO 24 I=1,30
CALL BPTR (P,X(J+1),T(J+1))
CALL ENTR1(T(J+1),X(J+1),HL(J+1))
*NEWTON RAPHSON METHOD IS USED TO CALC. L(J+1) AND X(J+1) .
XP1P=X(J+1)+0.01
XM1P=X(J+1)-0.01
IF(XP1P-1.)20,20,?1
21 XP1P=1.
DX=1.-XM1P
GO TO 22
20 DX=0.02
22 CALL BPTR(P,XP1P,TP1P)
CALL BPTR(P,XM1P,TM1P)
CALL ENTR1(TP1P,XP1P,HP1P)
CALL ENTR1(TM1P,XM1P,HM1P)
DHDX=(HP1P-HM1P)/DX
A=X(J+1)-Y(J)
E=L(J+1)
C=HL(J+1)-HV(J)
G=E*DHDX
DET=A*G-E*C
A11=G/DET
A12=-E/DET
A21=-C/DET
A22=A/DET
F1=A*E+(Y(J-1)-Y(J))*V(J-1)+(Y(J)-X(J))*L(J)
F2=E*C+V(J-1)*(HV(J-1)-HV(J))+L(J)*(HV(J)-HL(J))
DL=A11*F1+A12*F2
DXJ=A21*F1+A22*F2
L(J+1)=L(J+1)-DL
X(J+1)=X(J+1)-DXJ
IF(X(J+1).GT.1.0)X(J+1)=1.0
IF(ABS(DL)-10.000)23,23,24
23 IF(ABS(DXJ)-0.005)25,25,24
24 CONTINUE
PRINT 19,M
19 FORMAT(3X,*DIDNT CONVERGED ON X AND L AT PLATE NO.*,I3)
25 V(J)=L(J+1)+V(J-1)-L(J)
*FEED PLATE CHECK AND CALCULATIONS
IF(T(J+1)-TF)65,66,66
65 NFP=NFP+1
IF(NFP-1)67,67,66
DIST2830
DIST2840
DIST2850
DIST2860
DIST2870
DIST2880
DIST2890
DIST2900
DIST2910
DIST2920
DIST2930
DIST2940
DIST2950
DIST2960
DIST2970
DIST2980
DIST2990
DIST3000
DIST3010
DIST3020
DIST3030
DIST3040
DIST3050
DIST3060
DIST3070
DIST3080
DIST3090
DIST3100
DIST3110
DIST3120
DIST3130
DIST3140
DIST3150
DIST3160
DIST3170
DIST3180
DIST3190
DIST3200
DIST3210
DIST3220
DIST3230
DIST3240
DIST3250
DIST3260
DIST3270
DIST3280
DIST3290
DIST3300
DIST3310
DIST3320
DIST3330
DIST3340
DIST3350
DIST3360
DIST3370
DIST3380
DIST3390

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67 PRINT 16,J,M
16 FORMAT(/3X,*FEED ENTERS BETWEEN PLATES=*,I3,* AND *,I2)
   SL=L(J+1)
   SV=V(J)
   L(J+1)=L(J+1)-FL
   V(J)=V(J)+FV
   X(J+1)=(SL*X(J+1)-FL*XF2)/L(J+1)
   IF(X(J+1).GT.1.0)X(J+1)=1.0
   Y(J)=(SV*Y(J)+FV*Y2)/V(J)
   IF(Y(J).GT.1.0)Y(J)=1.0
   CALL BPTR(P,X(J+1),T(J+1))
   CALL ENTR1(T(J+1),X(J+1),HL(J+1))
66 CALL VKCR(P,T(J+1),KSO2,KSO3)
   Y(J+1)=KSO2*X(J+1)
   IF(Y(J+1).GT.1.0)Y(J+1)=1.0
   Y3=1.-Y(J+1)
   CALL ENTR2(T(J+1),Y(J+1),Y3,HV(J+1))
*FIRST GUESS FOR V(J+1) - NEXT J.
   V(J+1)=V(J)
*CHECK FOR TOP PLATE
   IF(Y(J)-XD)10,68,68
10 IF(X(J+1)-X(J)-0.001)11,11,60
60 CONTINUE
* IF DO LOOP COMPLETED THERE ARE TOO MANY STAGES
   PRINT 73,M
73 FORMAT(/3X,*TOO MANY STAGES.CALCULATIONS STOPPED AT M=*,I3)
   GO TO 68
11 PRINT 17
17 FORMAT(/3X,*NO MORE ENRICHMENT. CALC. STOPPED AT THIS POINT.*)
*FNAL PLATE CALCULATION
*CHECK AND CALC. MISMATCH AT THE TOP
68 DY=Y(J)-XD
   DV=V(J)-(L(J+1)+D)
*CALC. COOLING LOAD QC.
   QC=QR+F*HF-D*HD-B*HB
   QR=QR/3.6E3
   QC=QC/3.6E3
   M=M-1
   PD=P
   PB=P
   TM=T(M)
   HLM=HL(M)
   YM=Y(M)
   F=F/3600.
   B=B/3600.
   D=D/3600.
   IF(IFP.EQ.0)GO TO 1000
   PRINT 71,B,XB,TB,QR,F,XF,TF,D,XD,TD,QC
71)FORMAT(3X,*OUTPUT=
13X,*REBOILER= B=*,E11.4,3X,3HXF=,F5.3,3X,3HTB=,F5.1,3X,3HQR=,E11.4
2,/* FEED= F=*,E11.4,3X,3HXF=,F5.3,3X,3HTF=,F5.1,/3X,*CONDENS
3ER=D=*, E11.4,3X,3HXD=,F5.3,3X,3HTD=,F5.1,3X,3HQC=,E11.4)
   PRINT 72
   PRINT 74,(J,T(J),L(J),X(J),HL(J),V(J),Y(J),HV(J),J=1,M)
72)FORMAT(3X,*PLATES CONDITIONS
1* J T L X HL V
2 Y HV*)

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DIST3400
DIST3410
DIST3420
DIST3430
DIST3440
DIST3450
DIST3460
DIST3470
DIST3480
DIST3490
DIST3500
DIST3510
DIST3520
DIST3530
DIST3540
DIST3550
DIST3560
*DIST3570
DIST3580
*DIST3590
DIST3600
DIST3610
DIST3620
*DIST3630
DIST3640
DIST3650
DIST3660
DIST3670
DIST3680
*DIST3690
*DIST3700
DIST3710
DIST3720
*DIST3730
DIST3740
DIST3750
DIST3760
DIST3770
DIST3780
DIST3790
DIST3800
DIST3810
DIST3820
DIST3830
DIST3840
DIST3850
DIST3860
DIST3870
*/DIST3880
DIST3890
DIST3900
DIST3910
DIST3920
DIST3930
*/DIST3940
DIST3950
DIST3960

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740FORMAT(/3X,I2,3X,F5.1,3X,E11.4,3X,F5.3,3X,E11.4,3X,E11.4,3X,F5.3,3DIST3970
1X,E11.4) DIST3980
PRINT 75,M,DY,DV DIST3990
750FORMAT(3X,*NO.OF PLATES M=*,I2,3X,*DEVIATION FROM XD=*,F6.4,3X,*DEDIST4000
VIATION FROM V=*,E11.4/) DIST4010
1000 RETURN DIST4020
END DIST4030
```

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SUBROUTINE STC(QAAN,R2,T10,T30,R4,RATIO,ATGP2,BFWA1,BFWA2,TGP2)  STC  10
*****STC  20
*
*
*   UPDATED 4/15,78
*   STEAM TURBINE CALC.
*
*****STC  70
*CALCULATIONS ARE MADE FOR A CONVENTIONAL CROSS-COMPOUND TYPE TURBINE *STC  80
*WITH HIGH BACK-PRESSURE. REF= GE DOCUMENTATION ON THE BLACK-HILLS PROJ*STC  90
*THE BLACK-HILLS DESIGN (250MW,1800PSI,1000F/1000F) IS TAKEN AS THE *STC 100
*BASE DESIGN. ACCORDING TO BFWIL THE NEW DESIGN IS DERIVED BY DIRECT *STC 110
*PROPORTION TO THE BASE DESIGN. IT ALSO PROVIDE FOR ABSORBING THE LOW- *STC 120
*TEMP. HEAT AVAILABLE FROM THE STORAGE (BFWHL) AND TO PROVIDE THE NECE- *STC 130
*SSARY EXTRACTIONS OF STEAM FOR REBOILER (QRFS) AND VAPORIZER (VAP1L) *STC 140
*AT THE HTS-STORAGE.
*
*AFTER THE NEW DESIGN IS ESTABLISHED THE DAY TIME GENERATION IS DETERM- *STC 160
*IND AND BECOMES THE *TURBINE RATING*
*
*THE NIGHT OPERATION IS DETERMINED ACCORDING TO QAAN BY DIRECT PROPORTN *STC 180
*TO THE DAY TIME OPERATION. THE TURBINE IS SPLIT INTO TWO SEPARATE TUR *STC 190
*BINES, A SMALL ONE TO RUN AT FULL LOAD DURING 16 HRS AND A LARGE ONE, *STC 200
*WHICH RUNS AT 3.5 PERCENT OF DAYTIME FLOW TO KEEP IT HOT AND TURNING *STC 210
*BUT PRODUCING NO ELECTRICITY. THIS INCREASES EFFICIENCY BY AVOIDING *STC 220
*FLOWS FAR BELOW DESIGN. IN ADDITION TO REGULAR DISCHARGE, A SEASONAL *STC 230
*STORAGE CASE IS STUDIED WHERE DISCHARGE IS AT THE REGULAR DAYTIME RATE *STC 240
*OF POWER OUTPUT
*
*NOTE-STREAM NUMBERS (EXCEPT THOSE IN CALL) ARE FOR THE STEAM CYCLE AND *STC 260
*SHOULD NOT BE CONFUSED WITH PROCESS STREAMS.
*
*NOTE-DATA ARE GIVEN AND CALCULATIONS ARE MADE IN BRITISH UNITS. ALL *STC 280
*PARAMETERS SPECIFIED BY CALLING ROUTINE OR BY COMMON BLOCKS ARE *STC 290
*CONVERTED TO BRITISH UNITS (FLOW-(LB/HR), ENTHALPIES-(BTU/LB), HEAT LOAD *STC 300
*-(BTU/HR), PRESSURE-(PSI), TEMP-(F), ETC.)
*
*NOMENCLATURE=
*
*   A      TOTAL WATER FLOW INTO BOILER -NEW DESIGN
*   AD     TOTAL WATER FLOW INTO BOILER -DAY TIME
*   AN     TOTAL WATER FLOW INTO BOILER -NIGHT TIME
*   AO     BLACK-HILLS (IH) TOTAL WATER FLOW TO BOILER
*   ATGP   ARRAY FOR TOTAL GENERATED POWER
*   ATGP2  TGP OF SMALL TURBINE (16 HOUR OPERATION)
*   B      BH LOW PRESSURE EXTRACTION AT 86.7PSI
*   BFW    BOILER FEED WATER FLOW
*   BFWA   ARRAY FOR BOILER FEED WATER AT NIGHT
*   BFWA1  TOTAL BFW FLOW FOR NORMAL 16 HR OUTPUT
*   BFWA2  BFW FOR SEASONAL STORAGE, (100 MW OUTPUT AT NIGHT)
*   BFWF   BOILER FEED WATER FLOW FACTOR
*   BFWHL  BOILER FEED WATER HEAT LOAD (IN COMMON HTHEL)
*   C      BH LOW PRESSURE EXTRACTION AT 28.5PSI
*   C1L    CONDENSER 1 HEAT LOAD (IN COMMON HTHEL)
*   D      BH LOW PRESSURE EXTRACTION AT 14.3PSI
*   EC     HEAT RATE (BTU/HR) FOR STEAM THROUGH LP TURBINE
*   FACTOR FACTOR FOR CONVERTING FLOW INTO ENTHALPY IN KJ/S.
*   FH     STEAM EXTRACT FROM HIGH PRESSURE TURBINE
*   FHF    STEAM EXTRACT FROM HIGH PRESSURE TURBINE FACTOR
*   FI     STEAM EXTRACT FROM INTER. PRESSURE TURBINE
*   FIF    STEAM EXTRACT FROM INTER. PRESSURE TURBINE FACTOR

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*	FIF1	STEAM EXTRACT FROM ITER.PRESSURE TURBINE FACTOR IN EQ-1	*STC	550
*	FIF2	STEAM EXTRACT FROM ITER.PRESSURE TURBINE FACTOR IN EQ-2	*STC	560
*	FIP	STEAM FLOW THROUGH ITER.PRESSURE TURBINE	*STC	570
*	FIPF	STEAM FLOW THROUGH ITER.PRESSURE TURBINE FACTOR	*STC	580
*	FIPV	STEAM FLOW THROUGH ITER.PRESSURE TURBINE VALVE	*STC	590
*	FLP	FLOW THROUGH LP TURBINE	*STC	600
*	FLPF	FLOW THROUGH LP TURBINE FACTOR	*STC	610
*	GPHP	GROSS PRODUCTION (MWE) OF HIGH PRESSURE TURBINE (NEW)	*STC	620
*	GPHPO	GROSS PRODUCTION (MWE) OF HIGH PRESSURE TURBINE (BH)	*STC	630
*	GPLP	GROSS PRODUCTION OF LOW PRESSURE TURBINE (NEW DESIGN)	*STC	640
*	GPLPO	GROSS PRODUCTION OF LOW PRESSURE TURBINE (BH)	*STC	650
*	H	ENTHALPY OF ORIGINAL BH SL6 (AT 162.4PSI)	*STC	660
*	HB	ENTHALPY OF B	*STC	670
*	HC	ENTHALPY OF C	*STC	680
*	HD	ENTHALPY OF D	*STC	690
*	HE1L	HEAT EXCHANGER 1 LOAD (IN COMMON HTHEL)	*STC	700
*	H1-H16	ENTHALPIES AT VARIOUS LOCATIONS (SEE SCHEME)	*STC	710
*	I	DO-LOOP INDEX FOR DISCHARGE RATE	*STC	720
*	L	INDEX TO RATIO POWER TO 100MW	*STC	730
*	OEC	BH OVERALL HEAT (BTU/HR) CARRIED BY LP TURBINE STEAM.	*STC	740
*	OFL	BH LOW PRESSURE STEAM FLOW INTO CONDENSER	*STC	750
*	P12	PRESSURE STREAM 12 IN STEAM CYCLE (PSIA)	*STC	760
*	Q	HEAT ABSORBED BY STEAM (DAY-RECEIVER,NIGHT-REACTORS)	*STC	770
*	QAN	QAN SCALED BY R2	*STC	780
*	QAAN	Q AVAILABLE AT NIGHT -CALL STR PARAMETER	*STC	790
*	QBIGAN	Q IN LARGE TURBINE AT NIGHT (KJ/S)	*STC	800
*	QSMLAN	Q IN SMALL TURBINE AT NIGHT (KJ/S)	*STC	810
*	QFST	Q FROM STORAGE TOWER	*STC	820
*	QRES	Q REBOILER FROM STEAM (IN COMMON HTHEL)	*STC	830
*	R	RATIO OF NEW DESIGN A TO BH DESIGN AO (R=A/AO)	*STC	840
*	RATIO	RATIO OF HEAT ABSORBED IN STEAM RECEIVER TO STORAGE (TQA)	*STC	850
*	RCL	REBOILER-CONDENSER LOAD (IN COMMON HTHEL)	*STC	860
*	RHTR	REHEATER FLOW	*STC	870
*	RHTRF	REHEATER FLOW FACTOR	*STC	880
*	R1	RATIO OF FLOW AT NIGHT TO FLOW AT DAY (R1=AN/AO)	*STC	890
*	R2	RATIO FOR POWER AT 100MW	*STC	900
*	R4	RATIO FOR NIGHT-TIME POWER OF 100MW	*STC	910
*	SL10-SL60	STEAM LEAKS BH-DESIGN (SEE SCHEME)	*STC	920
*	SL1-SL6	STEAM LEAKS NEW DESIGN (SEE SCHEME)	*STC	930
*	SPLIT	SPLIT BETWEEN LARGE AND SMALL TURBINES	*STC	940
*	TE	TOTAL ENERGY (BTU) AVAILABLE AT NIGHT	*STC	950
*	TGP	TOTAL GROSS ELECTRIC PRODUCTION (MWE) NEW DESIGN	*STC	960
*	TGPD	TOTAL GENERATED POWER DURING THE DAY	*STC	970
*	TIME	PERIOD OF TIME QAN CAN SUPPLY 100.MW-E	STC	980
*	TMIN	MIN T ACHIEVABLE IN THE SYSTEM (K)	*STC	990
*	TPNF	THREE AND A HALF PERCENT OF NOMINAL FLOW (O. GENERATION)	*STC	1000
*	TQA	TOTAL Q AVAILABLE-STORAGE RECEIVER CAPACITY(MWT)	*STC	1010
*	TRIMMER	TRIMMER HEAT LOAD (IN COMMON HTHEL)	*STC	1020
*	T10	TEMP STREAM 10 IN STORAGE CYCLE (K)	*STC	1030
*	T12	TEMP STREAM 12 IN STEAM CYCLE (F)	*STC	1040
*	T15	TEMP STREAM 15 IN STEAM CYCLE (F)	*STC	1050
*	T30	TEMP. STREAM 30 IN STORAGE CYCLE (K)	*STC	1060
*	VAP1L	VAPRZ-1 HEAT LOAD (IN COMMON HTHEL)	*STC	1070
*	VPDS	STEAM FLOW TO VAPORIZER AND DIST.COL. AT HTS-STORAGE	*STC	1080
*	*****	*****	*STC	1090
*		DIMENSION ATGP(3),BFWA(3)	STC	1100
*		DIMENSION RA1A(15),BFA(15)	STC	1110

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COMMON/HTHEL/C1L,VAP1L,HE1L,RCL,BFWHL      ,TRIMMER,QRFS          STC 1120
COMMON/LAHTV/BFWCT,TMIN                    STC 1130
*BASIC TQA=230.4W HOWEVER, DIRECT STEAM TOWER IS SCALED FOR 2339MW-E *STC 1140
DATA TQA/230./
DATA H1,H2,   H4,H5,H6,H7,H8,H9,H10/1480.1,1344.4,   1521.6,139 STC 1160
14.3,334.9,332.1,341.,350.2,436.7/              STC 1170
DATA OFL,B,C,D,HB,HC,HD,H/1729723.,115729.,70436.,107501.,1333.3, STC 1180
11233.,1180.8,1398.8/                          STC 1190
*BASIC DATA OF THE BLACK HILL TURBINE(1800PSIA, 1000F/1000F) *STC 1200
DATA AO,SL10,SL20,SL30,SL40,SL50,SL60,GPHPO,GPLPO/2373398.,2791., STC 1210
1811.,23984.,9226.,3323.,3667.,167.4,164.5/    STC 1220
*STEAM CYCLE T AND H CALCULATED USING HTS SPECIFICATIONS *STC 1230
T15=1.8*(T10-10.)-460.                          STC 1240
H15=1.011*T15-34.21                             STC 1250
T12=1.8*TMIN-460.                               STC 1260
H13=.9975*T12-31.78                             STC 1270
P12=.0490*EXP(.0291*(T12))                      STC 1280
H12=1038.+49.*ALOG(P12)                         STC 1290
H14=H13+1.4                                       STC 1300
PRINT 13,TMIN,H12,P12                            STC 1310
13 FORMAT(2X,*TMIN(K)= *,F4.0,5X,*H12(RTU/LB)= *,F5.0,5X,*P12(PSIA)= STC 1320
1*,F6.3)                                          STC 1330
* DAY OPERATION *STC 1340
L=0                                               STC 1350
QFST=TQA                                         STC 1360
FACTOR=3600./1.0551/(H15-H14)                  STC 1370
BFW=BFWHL*FACTOR                                STC 1380
VPDS=(VAP1L+QRFS)*3.6E6/1055.1/(H5-H6)        STC 1390
SL4F=SL40/AO                                     STC 1400
FHF=(H10-H8),(H2-H9)                            STC 1410
FIF1=(H7-SL4F*H2-FHF*H9)/H5                    STC 1420
DO 17 K=1,15                                     STC 1430
7 FIF2=(BFW*H15+VPDS*H6)/H5                    STC 1440
A=(BFW+VPDS-FIF2)/(1.-SL4F-FHF-FIF1)          STC 1450
FH=FHF*A                                         STC 1460
FI=FIF1*A-FIF2                                  STC 1470
R=A/AO                                           STC 1480
AD=A                                             STC 1490
SL1=SL10*R                                       STC 1500
SL2=SL20*R                                       STC 1510
SL3=SL30*R                                       STC 1520
SL4=SL40*R                                       STC 1530
SL5=SL50*R                                       STC 1540
SL6=SL60*R                                       STC 1550
RHTR=A-SL1-SL2-SL4-SL5-FH-SL3                 STC 1560
FIPV=RHTP+SL1                                    STC 1570
FIP=FIPV+SL3                                     STC 1580
FLP=FIP-SL6-FI-VPDS                             STC 1590
*HEAT ABS. BY STEAM.                            STC 1600
Q=(A*(H1-H10)+RHTR*(H4-H2))*1055.1/3.6E9      STC 1610
RATIO=Q/QFST                                     STC 1620
IF(L.GT.0)GO TO 5                                STC 1630
RATIA(K)=RATIO                                  STC 1640
IF(K.GT.1) GO TO 22                              STC 1650
BFA(K)=BFW                                       STC 1660
BFW=BFW+40000.                                  STC 1670
BFA(K+1)=BFW                                    STC 1680

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GO TO 17
22 DCH=(RATIA(K)-RATIA(K-1))/(BFA(K)-BFA(K-1))
DBFW=(RATIA(K)-1.05)/DCH
BFA(K+1)=BFA(K)-DBFW
BFW=BFA(K+1)
IF(DBFW.LT.1E-05)GO TO 5
17 CONTINUE
PRINT 24, DBFW
24 FORMAT(/3X,*NO CONVERGENCE ON BFW, LAST DELTA BFW= *,F10.3)
5 DEC=OFL*(H-H12)+B*(H-HB)+C*(H-HC)+D*(H-HD)
EC=FLP*(H5-H12)
GPHP=GPHPD*R
GPLP=GPLPD*EC/DEC
TGP=GPHP+GPLP
L=L+1
IF(L.GT.1)GO TO 23
R2=1./(1.+RATIO)
BFW=BFW*R2
VPDS=VPDS*R2
QFST=QFST*R2
QAN=QAN*R2
GO TO 7
23 BFW=BFW/FACTOR
TGPD=TGP
BFWHL=BFW
PRINT 2
2 FORMAT(/3X,* DAY-TIME OPERATION.*)
PRINT 1,A,SL1,SL2,SL3,SL4,SL5,FH,RHTR,FIPV,FIP,SL6,F1,VPDS,FLP,BFW
1 FORMAT(
1/3X,*WATER TO BOILER *,F1).1,
2/3X,*SEAL LEAK - 1 *,F10.1,
3/3X,*SEAL LEAK - 2 *,F10.1,
4/3X,*SEAL LEAK - 3 *,F10.1,
5/3X,*SEAL LEAK - 4 *,F10.1,
6/3X,*SEAL LEAK - 5 *,F10.1,
7/3X,*HP - EXTRACTION *,F10.1,
8/3X,*REHEATER FLOW *,F10.1,
9/3X,*IP-FLOW AT VALVE *,F10.1,
A/3X,*IP TOTAL FLOW *,F10.1,
B/3X,*SEAL LEAK - 6 *,F10.1,
C/3X,*IP EXTRACTION *,F10.1,
D/3X,*VAP.+DIST. STEAM *,F10.1,
E/3X,*LP TOTAL FLOW *,F10.1,
F/3X,*TOTAL CONDENSATE *,F10.1)
PRINT 9,RATIO
9 FORMAT(/3X,*DIRECT STEAM GEN. TO STORAGE RATIO=*,F6.4)
PRINT 14,GPHP,GPLP,TGP
14 FORMAT(
1/3X,*POWER GENERATED AT HP TURBINE=*,F6.2,
2/3X,*POWER GENERATED AT IP TURBINE=*,F6.2,
3/3X,*TOTAL POWER GENERATED =*,F6.2)
*NIIGHT OPERATION
PRINT 2
2 FORMAT(/3X,*NIGHT-TIME OPERATION*)
RHTRF=1.-((SL10+SL20+SL30+SL40+SL50)/AO-FHF)
FIPF=RHTRF+(SL10+SL30)/AO
T15=1.8*(T30-10.)-450.

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```

STC 1690
STC 1700
STC 1710
STC 1720
STC 1730
STC 1740
STC 1750
STC 1760
STC 1770
STC 1780
STC 1790
STC 1800
STC 1810
STC 1820
STC 1830
STC 1840
STC 1850
STC 1860
STC 1870
STC 1880
STC 1890
STC 1900
STC 1910
STC 1920
STC 1930
STC 1940
STC 1950
STC 1960
STC 1970
STC 1980
STC 1990
STC 2000
STC 2010
STC 2020
STC 2030
STC 2040
STC 2050
STC 2060
STC 2070
STC 2080
STC 2090
STC 2100
STC 2110
STC 2120
STC 2130
STC 2140
STC 2150
STC 2160
STC 2170
STC 2180
STC 2190
*STC 2200
STC 2210
STC 2220
STC 2230
STC 2240
STC 2250

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H15=1.011*T15-24.21
FIF=((H7-H15)-SL40/AO*(H2-H15)-FHF*(H9-H15))/(H5-H15)
FLPF=FIPF-SL60/AO-FIF
BFWF=FLPF+(SL20+SL50+SL60)/AO
*TOTAL ENERGY AT NIGHT = QAN*16(HRS)
TE=QAN*3600.*16./1.0551
*ASSUME 3.5 P.C.FLOW IS OBTAINED BY SUPPLYING 5 P.C. OF HEAT.
Q=QFST*RATIO*1000.
*TURBINE IS SPLIT INTO SMALL AND LARGE TURBINES
SPLIT=.26*(RATIO-1.)+.5
QBIGAN=(Q-QAN)*3600./1.0551/0.965*0.050*SPLIT
QSMLAN=TE-QBIGAN*16.
TPNF=QBIGAN/(RHTRF*(H4-H2)+(H1-H10))
A=TPNF
Q=QBIGAN
PRINT 6
6 FORMAT(/3X,*LARGE TURBINE AT 3.5P.C. OF DAY-TIME FLOW*)
DO 4 I=1,3
IF(I-2)8,19,20
19 PRINT 10
10 FORMAT(/3X,*POWER RATE AT SMALL TURBINE DURING 16 HRS AT NIGHT.*)
Q=QSMLAN/16.
GO TO 11
20 PRINT 21
21 FORMAT(/3X,*100 MW-E TURBINE AT SEASONAL STORAGE OP. CONDITIONS*)
Q=TGP0*Q/TGP
TIME=TE/Q
R4=16./TIME
PRINT 15,TIME,R4
15 FORMAT(/3X,*DISCHARGE AT FULL LOAD*,F6.3,*HRS. NEEDS*,F6.3,* DAYS
10F STORAGE TO*,/3X,*RUN 16 HRS AT FULL LOAD*)
11 A=Q/(RHTRF*(H4-H2)+(H1-H10))
8 AN=A
*ALL FLOWS RATIOED TO FLOW INTO BOILER
RHTR=RHTRF*A
FIP=FIPF*A
FLP=FLPF*A
BFW=BFWF*A
FI=FIF*A
FH=FHF*A
VPDS=Q.
R=A/AO
R1=AN/AD
PRINT 12,R,R1
12 FORMAT(/3X,2HR=,E10.4,3X,3HR1=,E10.4)
SL1=SL10*R
SL2=SL20*R
SL3=SL30*R
SL4=SL40*R
SL5=SL50*R
SL6=SL60*R
FIPV=RHTR+SL1
PRINT 1,A,SL1,SL2,SL3,SL4,SL5,FH,RHTR,FIPV,FIP,SL6,FI,VPDS,FLP,BFW
EC=FLP*(H5-H12)
GPHP=GPHPO*R
GPLP=GPLPO*EC/OEC
TGP=GPHP+GPLF

```

```

STC 2260
STC 2270
STC 2280
STC 2290
*STC 2300
STC 2310
*STC 2320
STC 2330
*STC 2340
STC 2350
STC 2360
STC 2370
STC 2380
STC 2390
STC 2400
STC 2410
STC 2420
STC 2430
STC 2440
STC 2450
STC 2460
STC 2470
STC 2480
STC 2490
STC 2500
STC 2510
STC 2520
STC 2530
STC 2540
STC 2550
STC 2560
STC 2570
STC 2580
*STC 2590
STC 2600
STC 2610
STC 2620
STC 2630
STC 2640
STC 2650
STC 2660
STC 2670
STC 2680
STC 2690
STC 2700
STC 2710
STC 2720
STC 2730
STC 2740
STC 2750
STC 2760
STC 2770
STC 2780
STC 2790
STC 2800
STC 2810
STC 2820

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```
PRINT14,GPHP,GPLP,TGP          STC 2830
ATGP(I)=TGP                     STC 2840
BFWA(I)=BFW                     STC 2850
4 CONTINUE                      STC 2860
*ONLY THE SMALL TURBINE POWER IS SENT BACK TO MEBP *STC 2870
ATGP2=ATGP(2)                  STC 2880
BFWA1=BFWA(1)+BFWA(2)         STC 2890
BFWA2=BFWA(3)                 STC 2900
FACTOR=3600./1.0551/(H15-H14) STC 2910
BFWA1=BFWA1/FACTOR            STC 2920
BFWA2=BFWA2/FACTOR            STC 2930
RETURN                          STC 2940
END                              STC 2950
```



```

SUBROUTINE CLR(I,J,K,CL)                                CLR 10
*****                                                CLR 20
*                                                    *CLR 30
*   UPDATED 4/15/78                                    *CLR 40
*           CLR - CONDENSER LOAD ROUTINE                *CLR 50
*                                                    *CLR 60
*****                                                CLR 70
*ROUTINE IS USED TO CALC. CONDENSER LOAD FOR GIVEN INPUT GAS STREAM AND*CLR 80
*GIVEN OUTPUT TEMP. IT ALSO SET THE RECORD FOR BOTH LIQUID AND GAS *CLR 90
*LEAVING STREAMS.                                     *CLR 100
*   ROUTINE IS CALLED BY *CALL CCR(NI,NG,NL,CL)* * WHERE NI IS NO. *CLR 110
*   OF INPUT STREAM, NG IS NO. OF GAS EXITING STREAM,NL IS LIQUID OUT*CLR 120
*   - PUT STREAM, CL-CONDENSER LOAD .                 *CLR 130
*   ROUTINE HAS ACCESS TO THE MAIN PROGRAM ARRAYS=F,P,T,H,X1,X2,X3 *CLR 140
*ROUTINE USES CCL FUNCTION TO DETERMINE THE LOAD      *CLR 150
*   ROUTINE ASSUMES CONDENSATION AT CONSTANT PRESSURE AND SET = *CLR 160
*   P(NL)=P(NG)=P(NI).                                *CLR 170
*   ROUTINE ASSUMES THAT BOTH T(NI) AND T(NG) ARE GIVEN. *CLR 180
*                                                    *CLR 190
*NOMENCLATURE=                                       *CLR 200
*   CL      CONDENSER LOAD (KJ/S)                      *CLR 210
*   F      FLOW(KMOL/SEC)                             *CLR 220
*   H      ENTHALPY,(KJ/KMOL)                         *CLR 230
*   I      INPUT GAS STREAM INDEX                     *CLR 240
*   J      OUTPUT GAS STREAM INDEX                    *CLR 250
*   K      OUTPUT LIQ. STREAM INDEX                   *CLR 260
*   NG     OUTPUT GAS STREAM INDEX (USED FOR PRINTIG ONLY) *CLR 270
*   NI     INPUT GAS STREAM INDEX 0(USED FOR PRINTIG ONLY) *CLR 280
*   NL     OUTPUT LIQ. STREAM INDEX (USED FOR PRINTIG ONLY) *CLR 290
*   P      PRESSURE(BAR)                              *CLR 300
*   T      TEMP.(K)                                   *CLR 310
*   TJ     EX'T TEMP. AS SPECIFIED TO CCL              *CLR 320
*   X1     OX'GEN CONTENT (MOLE FRACTION)             *CLR 330
*   X2     SO2 CONTENT (MOLE FR.)                    *CLR 340
*   X3     SO3 CONTENT (MOLE FR.)                    *CLR 350
*****                                                CLR 360
*                                                    *CLR 370
*   COMMON/STREAM/F(60),P(60),T(60),H(60),X1(60),X2(60),X3(60) CLR 380
*                                                    *CLR 390
*   PRINT 50,I,J,K,T(J)                               CLR 400
*   50 FORMAT(/3X,*CLR ROUTINE*/3X,*INPUTS= NI=*,I2,3X,3HNG=I2,3X,3HNL=,CLR 410
*   I12,3X,      7HT(OUT)=,F7.2)                    CLR 420
* CONDENSER LOAD CALCS.                               *CLR 430
*   TJ=T(J)                                           CLR 440
*   CL=CCL(I,J,K,TJ)                                  CLR 450
*   END OF ROUTINE.RETURN AFTER SUCCESSFUL CALCULATIONS *CLR 460
*   T(K)=T(J)                                         CLR 470
*   PRINT 44                                           CLR 480
*   PRINT 55,I,F(I),X1(I),X2(I),X3(I),T(I),H(I)      CLR 490
*   PRINT 55,J,F(J),X1(J),X2(J),X3(J),T(J),H(J)      CLR 500
*   PRINT 55,K,F(K),X1(K),X2(K),X3(K),T(K),H(K)      CLR 510
*   PRINT 5,CL                                         CLR 520

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44 FORMAT(/3X,*RESULTS OF CLR  ROUTINE*/,5X,2HSN,1CX,1HF,8X,2HX1, CLR 530
    18X,2HX2,8X,2HX3,9X,1HT,9X,1HH) CLR 540
55 FORMAT(/6X,I2,5X,6F10.4) CLR 550
5  FORMAT(/3X,*CONDENSER LOAD= CL=*,E11.4) CLR 560
    RETURN CLR 570
    END CLR 580
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SUBROUTINE CTR(I,J,K,CL)                                CTR 10
*****CTR 20
*                                                       *CTR 30
*   UPDATED 4/15/78                                     *CTR 40
*   CTR - CONDENSER TEMP. ROUTINE.                     *CTR 50
*                                                       *CTR 60
*****CTR 70
*ROUTINE IS CALLED BY *CTR(NI,NG,NL,CL)*              *CTR 80
*ROUTINE CALCS. EXIT TEMP. FOR A CONDENSER WHOSE LOAD IS GIVEN. *CTR 90
*IN ADDITION THE ROUTINE CALCS. AND UPDATE THE STREAM FILE (EXIT STREAM)*CTR 100
*   ROUTINE IS CALLED BY *CALL CCR(NI,NG,NL,CL)* * WHERE NI IS NO. *CTR 110
*   OF INPUT STREAM, NG IS NO. OF GAS EXITING STREAM,NL IS LIQUID OUT*CTR 120
*   - PUT STREAM, CL=CONDENSER LOAD .                 *CTR 130
*   ROUTINE ASSUMES CONDENSATION AT CONSTANT PRESSURE AND SET = *CTR 140
*   P(NL)=P(NG)=P(NI).                               *CTR 150
*   ROUTINE ASSUMES THAT BOTH T(NI) AND T(NG) ARE GIVEN. HOWEVER, *CTR 160
*   *T(NG) IS CONSIDERED AS FIRST APPROXIMATION ONLY AND IS UPDATED. *CTR 170
*   ROUTINE HAS ACCESS TO THE MAIN PROGRAM ARRAYS=F,P,T,H,X1,X2,X3 *CTR 180
*ROUTINE USES THE FOLLOWING SUBROUTINES= VKCR,BPTR,CCL,RECOPY,ENTR2 *CTR 190
*                                                       *CTR 200
*NOMENCLATURE=                                         *CTR 210
*   BPT BUBBLE POINT TEMP.                            *CTR 220
*   CCL1 MAX. CL FOR T(J)=273. ALSO USED IN NR TO FIND T *CTR 230
*   CCL2 USED IN NR (=F*DH) TO FIND T                 *CTR 240
*   CL CONDENSER LOAD (KJ/S)                          *CTR 250
*   CLADP CONDENSER LOAD AT DEW POINT                 *CTR 260
*   DP DEW POINT (=DPT) IN CALL FOR VKCR             *CTR 270
*   DPF1 NR FUNCTION VALUE (FOR DPT) IN DO LOOP 15   *CTR 280
*   DPF2 NR FUNCTION VALUE (FOR DPT-1) IN DO LOOP 15 *CTR 290
*   DPT DEW POINT TEMP.                              *CTR 300
*   DT INCREMENT FOR DPT AS CALC. BY NR (DO LOOP 15) *CTR 310
*   EPST TOLERANCE FOR ACCEPTABLE DT                 *CTR 320
*   F FLOW (KMOL/HR)                                  *CTR 330
*   H ENTHALPY (KJ/KMOL)                              *CTR 340
*   I INPUT GAS STREAM INDEX                          *CTR 350
*   J OUTPUT GAS STREAM INDEX                         *CTR 360
*   K OUTPUT LIQ. STREAM INDEX                        *CTR 370
*   K2 VOLATILITY CONST. FOR SO2                     *CTR 380
*   K3 VOLATILITY CONST. FOR SO3                     *CTR 390
*   M NO.OF ITERATIONS IN DPT DO LOOP AND T DO LOOPS *CTR 400
*   N DO LOOP INDEX IN DPT CALCS.(15) AND IN T CALCS.(12,23) *CTR 410
*   NG OUTPUT GAS SREAM INDEX (USED IN PRINTING ONLY) *CTR 420
*   NI INPUT GAS STREAM INDEX (USED FOR PRINTING ONLY) *CTR 430
*   NL OUTPUT LIQ. STREAM INDEX (USED FOR PRINTING ONLY) *CTR 440
*   P PRESSURE (BAR)                                  *CTR 450
*   TJ GAS EXIT TEMP.                                 *CTR 460
*   X1 MOLE FRACTION O2                               *CTR 470
*   X2 MOLE FRACTION SO2                              *CTR 480
*   X3 MOLE FRACTION SO3                              *CTR 490
*****CTR 500
DIMENSION TJ(10)                                       CTR 510
COMMON/STREAM/F(60),P(60),T(60),H(60),X1(60),X2(60),X3(60) CTR 520

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```

REAL K2,K3                                CTR 530
DATA EPST,M/1.,10/                        CTR 540
PRINT 50,I,J,K,CL                          CTR 550
50 FORMAT(/3X,*CTR ROUTINE*/3X,*INPUTS= NI=*,I2,3X,3HNG=I2,3X,3HNL=,CTR 560
   I12,3X,3HCL=,E11.4,)                   CTR 570
*CHECK WHETHER CL IS NOT NEGATIVE . IF NEG. PRINT ERROR MASSEGE, IF 0*CTR 580
*SET STREAM NG EQ. 10 NI ANDSTREAMNL EQ. ZERO. *CTR 590
   IF(CL)1,2,3                             CTR 600
* 1- ERROR. CL CANT BE NEGATIVE            *CTR 610
   1 PRINT 4,I,CL                           CTR 620
   40FORMAT(/3X,*ERROR IN CONDENSER LOAD DATA. CL IS NEGATIVE. NI=*, CTR 630
   I12,3X,3HCL=,E11.4)                    CTR 640
   GO TO 100                                CTR 650
   2 CALL RECOPY(I,J)                       CTR 660
   CALL RECOPY(45,K)                       CTR 670
   GO TO 24                                  CTR 680
*CALC. CL MAX. AT T(J)=273.                CTR 690
   3 CCL1=CCL(I,J,K,273.)                  CTR 700
*CHECK IF SPECIFIED LOAD IS NOT TOO HIGH. *CTR 710
   IF(CCL1.GT.CL)GO TO 37                  CTR 720
*MAX. LOAD CALCS.                          *CTR 730
   T(J)=273.                                CTR 740
   PRINT 38                                 CTR 750
   38 FORMAT(/3X,*CONDENSER CANT ACCOMODATE SUCH LOAD DEMAND WITH THE SPCTR 760
   IECIFIED FLOW.*/3X,*RESULTS ARE GIVEN FOR MAX. POSSIBLE LOAD-CCL*)CTR 770
   GO TO 24                                  CTR 780
*FIND BUBBLE POINT. (IT IS NOT A TRUE BP. IT IS USED ONLY AS A FIRST *CTR 790
*APPROXIMATION FOR THE DEW POINT.) *CTR 800
   37 CALL BPTR(P(I),X2(I),JPT)            CTR 810
*FIND DPT-DEW POINT TEMP. (FIRST APPROX. FOR DPT IS BPT.) *CTR 820
   DPT=BPT                                  CTR 830
   DO 15 N=1,M                              CTR 840
   DP=DPT                                    CTR 850
   CALL VKCR(P(I),DP,K2,K3)                CTR 860
   DPF1=X2(I)/I2+X3(I)/K3-.                CTR 870
   DP=DP-1.                                  CTR 880
   CALL VKCR(P(I),DP,K2,K3)                CTR 890
   DPF2=X2(I)/K2+X3(I)/K3-.                CTR 900
   DT=DPF1/(DPF1-DPF2)                     CTR 910
   IF(ABS(DT)-50.)6,6,7                    CTR 920
   7 DT=50.0*DT/ABS(DT)                    CTR 930
   6 DPT=DPT-DT                             CTR 940
   IF(ABS(DT)-EPST)16,16,15                CTR 950
   15 CONTINUE                             CTR 960
*GET CLADP - CL AT DEW POINT. *CTR 970
   16 CALL RECOPY(I,J)                     CTR 980
   CALL RECOPY(45,K)                       CTR 990
   T(J)=DPT                                 CTR 1000
   CALL ENTR2(DPT,X2(J),X3(J),H(J))        CTR 1010
   CLADP=F(I)*(H(I)-H(J))                  CTR 1020
   CCL1=CLADP                              CTR 1030
*SELECT CONDENSER OR COOLER ROUTINE        CTR 1040
   IF(CLADP-CL)18,24,19                    CTR 1050
*                                           *CTR 1060
*                                           *CTR 1070
* EXIT TEMP. CALC. FOR COOLER. *CTR 1080
   19 CALL RECOPY(I,J)                     CTR 1090

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CALL RECOPY(45,K)
T(J)=DPT
DO 12 N=1,M
IF(T(J)-DPT)25,28,28
25 T(J)=DPT
28 TJ(N)=T(J)
CALL ENTR2(TJ(N),X2(J),X3(J),H(J))
CCL1=F(I)*(H(I)-H(J))
TJ(N)=TJ(N)-1.
CALL ENTR2(TJ(N),X2(J),X3(J),H(J))
CCL2=F(I)*(H(I)-H(J))
DT=(CL-CCL1)/(CCL1-CCL2)
IF(ABS(DT)-50.)32,32,33
33 DT=50.0*DT/ABS(DT)
32 T(J)=T(J)+DT
IF(ABS(DT)-EPST)26,26,12
12 CONTINUE
GO TO 8
* -EXIT TEMPS. CALCULATIONS. (CONDENSER).
*FIRST GUESS= T(J)=(DPT+BPT)/2.
18 T(J)=(DPT+BPT)/2.
21 DO 23 N=1,M
IF(T(J)-DPT)10,10,11
11 T(J)=DPT
10 TJ(N)=T(J)
CCL1=CCL(I,J,K,TJ(N))
TJ(N)=TJ(N)-1.
CCL2=CCL(I,J,K,TJ(N))
DT=(CL-CCL1)/(CCL1-CCL2)
IF(ABS(DT)-50.)34,34,35
35 DT=50.0*DT/ABS(DT)
34 T(J)=T(J)+DT
IF(ABS(DT)-EPST)26,26,23
23 CONTINUE
*NO CONVERGENCE ON T.
8 PRINT 27
27 FORMAT(/3X,*NO CONVERGENCE ON T(J) AND T(K) AT CTR*)
*
*LAST PASS THROUGH CCL
26 CCL1=CCL(I,J,K,T(J))
* 24- IS THE END OF ROUTINE.RETURN AFTER SUCCESSFUL CALCULATIONS
24 T(K)=T(J)
PRINT 44
PRINT 55,I,F(I),X1(I),X2(I),X3(I),T(I),H(I)
PRINT 55,J,F(J),X1(J),X2(J),X3(J),T(J),H(J)
PRINT 55,K,F(K),X1(K),X2(K),X3(K),T(K),H(K)
44 FORMAT(/3X,*RESULTS OF ITR ROUTINE*/,5X,2HSN,10X,1HF,8X,2HX1,
18X,2HX2,8X,2HX3,9X,1HT,9X,1HH)
55 FORMAT(/6X,*2,5X,6E10.4)
PRINT 9,CL,CCL1
9 FORMAT(/3X,*CONVERGENCE ACCURACY= CL=*,E11.4,3X,*COMPARE TO CCL=*,
1E11.4)
100 RETURN
END

```

```

CTR 1100
CTR 1110
CTR 1120
CTR 1130
CTR 1140
CTR 1150
CTR 1160
CTR 1170
CTR 1180
CTR 1190
CTR 1200
CTR 1210
CTR 1220
CTR 1230
CTR 1240
CTR 1250
CTR 1260
CTR 1270
*CTR 1280
CTR 1290
CTR 1300
CTR 1310
CTR 1320
CTR 1330
CTR 1340
CTR 1350
CTR 1360
CTR 1370
CTR 1380
CTR 1390
CTR 1400
CTR 1410
CTR 1420
CTR 1430
*CTR 1440
CTR 1450
CTR 1460
*CTR 1470
*CTR 1480
CTR 1490
*CTR 1500
CTR 1510
CTR 1520
CTR 1530
CTR 1540
CTR 1550
CTR 1560
CTR 1570
CTR 1580
CTR 1590
CTR 1600
CTR 1610
CTR 1620
CTR 1630

```





F(K)=F(I)	CCL 810
2 IF(F(K))9,100,100	CCL 820
9 IF(F(K)+0.01*F(I))1,10,10	CCL 830
10 F(K)=0.	CCL 840
F(J)=F(I)	CCL 850
GO TO 100	CCL 860
*TRY DIFF. INITIAL CONDITIONS. IF DOESNT HELP STOP PROG.	*CCL 870
1 CONTINUE	CCL 880
PRINT 6,F(I),F(J),F(K)	CCL 890
6 FORMAT(/3X,*FLOWS I,J,K, ARE=*,3(3X,F11.4))	CCL 900
PRINT 5	CCL 910
5 FORMAT(3X,*IGNORE CONDENSER. SET F(J)=F(I) AS IF NON-COND.*)	CCL 920
*CALCS. FOR NON-CONDENSIBLE FEED.	*CCL 930
11 X1(J)=X1(I)	CCL 940
X2(J)=X2(I)	CCL 950
X3(J)=X3(I)	CCL 960
F(J)=F(I)	CCL 970
CALL ENTR2(TJ,X2(J),X3(J),H(J))	CCL 980
CALL RECOPY'45,K)	CCL 990
CL=(H(I)-H(J))*F(I)	CCL 1000
CCL=CL	CCL 1010
PRINT 12,T(J),CL	CCL 1300
12 FORMAT(/3X,*CCL WAS CALLED TO CALC. FOR NONCONDENSIBLE MIXTURE. LOC	CCL 1310
1AD CALC. ON BASIS OF GA; ENTHALPY CHANGE ONLY. T(J)=*,F7.2,3X,3HCL	CCL 1320
2=,E11.4)	CCL 1330
100 RETURN	CCL 1020
1000 CONTINUE	CCL 1030
END	CCL 1040



```

SUBROUTINE FINDT(NS,J)                                FINT 10
*****FINT 20
*                                                    *FINT 30
*   UPDATED 4/15/78                                *FINT 40
*   FINDT - ROUTINE TO FIND T IF H IS GIVEN.        *FINT 50
*                                                    *FINT 60
*****FINT 70
*ROUTINE IS CALLED BY *FINDT(NS,NF) WHERE NS IS STATE INDICATOR (1 FOR *FINT 80
*LIQ. 2 FOR GAS) AND NF IS THE STREAM RECORD NO. IT HAS ACCESS TO ALL *FINT 90
*STREAM RECORDS. ROUTINE USES VALUE FOUND IN T(J) AS FIRST GUESS IN A *FINT 100
*NR SCHEME TO FIND THE EXACT VALUE OF THIS TEMP. *FINT 110
*ROUTINE USES THE FOLLOWING SUBROUTINES= ENTR1,ENTR2 *FINT 120
*   NOMENCLATURE= *FINT 130
*   DT      INCREMENT OF T(J) CALC.BY NR SCHEME *FINT 140
*   F       FLOW(KMOL/SEC) *FINT 150
*   H       ENTHALPY,(KJ/KMOL) *FINT 160
*   HH      ENTHALPY CORRESPOND TO T(J) *FINT 170
*   H1      ENTHALPY CORRESPOND TO T1 *FINT 180
*   I       INDEX IN DO LOOP 1 *FINT 190
*   J       NO. OF STREAM RECORD FOR WHICH T IS CALC. *FINT 200
*   NS      STATUS OF STREAM= LIQUID (1) OR GAS (2) *FINT 220
*   P       PRESSURE(BAR) *FINT 230
*   T       TEMP.(K) *FINT 240
*   T1      T(J)+1 *FINT 250
*   X1      OXYGEN CONTENT (MOLE FRACTION) *FINT 260
*   X2      SO2 CONTENT (MOLE FR.) *FINT 270
*   X3      SO3 CONTENT (MOLE FR.) *FINT 280
*                                                    *FINT 290
*****FINT 300
*                                                    *FINT 310
COMMON/STREAM/F(60),P(6),T(60),H(60),X1(60),X2(60),X3(60) FINT 320
DO 1 I=1,30 FINT 330
  T1=T(J)+1. FINT 340
  IF(NS-1)4,4,3 FINT 350
  3 CALL ENTR2(T(J),X2(J),X3(J),HH) FINT 360
  CALL ENTR2(T1, X2(J),X3(J),H1) FINT 370
  GO TO 5 FINT 380
  4 CALL ENTR1(T(J),X2(J),HH) FINT 390
  CALL ENTR1(T1, X2(J),H1) FINT 400
  5 DT=(HH-H(J))/(H1-HH) FINT 410
  T(J)=T(J)-DT FINT 420
  IF(ABS(DT)-0.01)2,2,1 FINT 430
  1 CONTINUE FINT 440
* NO CONVERGENCE ON T= PRINT MESSAGE. *FINT 450
  PRINT 6,T(J),HH,H1,H(J),J FINT 460
  6 FORMAT(/3X,*NO CONV. ON T= T(J)=*,F6.2,3X,3HHH=,E10.4,3X,3HH1=,E10 FINT 470
  1.4,3X,5HH(J)=,E10.4,3X,2HJ=,I2,*IN FINDT*) FINT 480
  2 RETURN FINT 490
  END FINT 500

```

```

SUBROUTINE RECOPY(I,J)
*****
*
*   UPDATED 4/15/78
*   RECOPY - RECORD COPYER.
*
*****
*ROUTINE CALLED BY CALL RECOPY(IIN,IOUT) WHERE IIN=RECORD TO COPY FROM
*AND IOUT=RECORD TO UPDATE.
*
*VARIABLES=
*   F      FLOW(KMOL/SEC)
*   H      ENTHALPY,(KJ/KMOL)
*   I      INPUT STREAM INDICATOR
*   J      OUTPUT STREAM INDICATOR
*   P      PRESSURE(BAR)
*   T      TEMP.(K)
*   X1     OXYGEN CONTENT (MOLE FRACTION)
*   X2     SO2 CONTENT (MOLE FR.)
*   X3     SO3 CONTENT (MOLE FR.)
*****
*
*
COMMON/STREAM/F(60),P(60),T(60),H(60),X1(60),X2(60),X3(60)
F(J)=F(I)
T(J)=T(I)
P(J)=P(I)
H(J)=H(I)
X1(J)=X1(I)
X2(J)=X2(I)
X3(J)=X3(I)
RETURN
END

```

```

COPY 10
COPY 20
COPY 30
COPY 40
COPY 50
COPY 60
COPY 70
COPY 80
COPY 90
COPY 100
COPY 110
COPY 120
COPY 130
COPY 140
COPY 170
COPY 180
COPY 190
COPY 200
COPY 210
COPY 220
COPY 230
COPY 240
COPY 250
COPY 260
COPY 270
COPY 280
COPY 290
COPY 300
COPY 310
COPY 320
COPY 330
COPY 340
COPY 350

```

```

FUNCTION TRKP(X,P,X1,X2,X3)
*****
*
*   UPDATED 4/15/78
*   TRKP - KP CONSTANT ROUTINE
*
*****
*ROUTINE IS CALLED BY HTR
*ROUTINE CALCS. KP FOR GIVEN X AND P.
*   NOMENCLATURE=
*   C   CONVERTED FRACTION X*X3
*   P   TOTAL PRESSURE
*   TRKP FUNCTION-TEMP. DEPENDENT REACTION KP CONSTANT
*   X1   O2 MOL. FR.
*   X2   SO2 MOL. FR.
*   X3   SO3 MOL. FR.
*****
*
C=X*X3
TRKP=(X2+C)/(X3-C)*SQRT(P*(2.*X1+C)/(2.+C))
RETURN
END

```

```

TRKP 10
*TRKP 20
*TRKP 30
*TRKP 40
*TRKP 50
*TRKP 60
*TRKP 70
*TRKP 80
*TRKP 90
*TRKP 100
*TRKP 105
*TRKP 110
*TRKP 120
-*TRKP 120
-*TRKP 131
-*TRKP 132
*TRKP 140
*TRKP 150
TRKP 160
TRKP 170
TRKP 180
TRKP 190

```

```

      FUNCTION TKP(X,P,X1,X2,(3)
*****TKP 10
*
*          TRKTKP - CONSTANT ROUTINE
*
*****TKP 20
*          *TKP 30
*          *TKP 40
*          *TKP 50
*****TKP 60
*ROUTINE IS CALLED BY LTR
*ROUTINE CALCS. KP FOR GIVEN X AND P. OXIDATION REACTION.
*          *TKP 70
*          *TKP 80
*          *TKP 90
*          *TKP 100
*          *TKP 110
*          *TKP 120
*          *TKP 130
*          *TKP 140
*          *TKP 150
*****TKP 160
*          *TKP 170
*          *TKP 180
*          *TKP 190
*          *TKP 200
*          *TKP 210
      C=X*X2
      TKP=(X3+C)/(X2-C)/SQRT(P*(2.*X1-C)/(2.-C))
      RETURN
      END

```

```

FUNCTION CP(T,Y1,Y2,Y3)
*****CP 10
*CP 20
*
*   UPDATED 4/17/78
*CP 30
* CP - SPACIFIC HEAT ROUTINE
*CP 40
*
*CP 50
*
*CP 60
*****CP 70
*ROUTINE CALCS. CP AT ANY GIVEN T AND COMPOSITION.
*CP 80
*CP AS FUNCTION OF TEMP. IS TAKEN ACCORDING TO EKLUND.
*CP 90
*(FOR EXACT REFERENCE SEE ENTG ROUTINE)
*CP 100
*   NOMENCLATURE=
*CP 110
*   CP      FUNCTIO-OVERALL SPECIFIC HEAT
*CP 120
*   CP1     SPECIFIC HEAT OF O2
*CP 130
*   CP2     SPECIFIC HEAT OF SO2
*CP 140
*   CP3     SPECIFIC HEAT OF SO3
*CP 150
*   T       SYSTEM TEMP.
*CP 160
*   Y1     MOL. FR. OF O2
*CP 170
*   Y2     MOL. FR. OF SO2
*CP 180
*   Y3     MOL. FR. OF SO3
*CP 190
*****CP 200
CP1=7.16+0.001*T-4.0E4/T**2
CP 210
CP2=10.38+2.54E-3*T-1.42E5/T**2
CP 220
CP3=13.7+6.42E-3*T-3.12E5/T**2
CP 230
CP=CP1*Y1+CP2*Y2+CP3*Y3
CP 240
RETURN
CP 250
END
CP 260

```

```
FUNCTION DHR(T) DHR 10
*****DHR 20
* DHR 30
*   UPDATED 4/15/78 DHR 40
*   DHR - HEAT OF REACTION ROUTINE DHR 50
* DHR 60
*****DHR 70
*ROUTINE CALCS. HEAT OF REACTION AT ANY T ACCORDING TO S DHR 80
*   DHR(T)=DHR(298K)+(H-PROD.-H-REAC.) AT T DHR 90
*   GIVEN= DHR(298K)=23523. CAL/MOLE (REF. EKLUND). DHR 100
* DHR 110
*NOMENCLATURE= DHR 120
*   DHR   FUNCTION-DELTA HEAT OF REACTION DHR 130
*   T     REACTION TEMP. DHR 140
*****DHR 150
DHR=23523.-7.6*T+1.69E-3*T**2+1.5E5/T-577.5 DHR 160
RETURN DHR 170
END DHR 180
```

```

SUBROUTINE ENTR1(T,X2,HL)
*****
*
*   UPDATED 4/15/78
*   ENTR1 - ENTHALPY OF LIQUID MIXTURE ROUTINE
*
*****
*   ROUTINE IS CALLED BY *CALL ENTR1(T,X2,HL)* WHERE T IS TEMP.(K),
*   X2-SO2 MOLE FR. (BOTH T AND X2 ARE SPECIFIED BY THE CALLING PROG)
*   HL-LIQUID MIXTURE ENTHALPY(KJ/KMOLE) TO BE CALCULATED.
*   IT IS ASSUMED THAT LIQ. MIXTURES CONTAIN ONLY SO2+SO3 AND BEHAVE
*   AS AN IDEAL MIXTURE.
*   ROUTINE CALL ENTR2 TO OBTAIN H(GAS MIXTURE) AND THEN IT CALL LHR
*   TO OBTAIN HEAT OF VAPORIZATION AT THE SAME TEMP.
*   H(LIQUIDE MIXTURE)=h(GAS)-LH(MIXTURE)
*   NOMENCLATURE=
*   HG      ENTHALPY OF GAS AT T AND COMPOSITION X2,X3
*   HL      ENTHALPY OF LIQ AT T AND COMPOSITION X2,X3
*   LH      LATENT HEAT OF STREAM AT T AND X2,X3 COMPOSITION
*   T       TEMP. OF STREAM
*   X2      MOLE FR. SO2
*   X3      MOLE FR. SO3
*****
REAL LH
X3=1.-X2
CALL ENTR2(T,X2,X3,HG)
CALL LHR(T,X2,LH)
HL=HG-LH
RETURN
END

```

ENTL 10  
 ENTL 20  
 ENTL 30  
 ENTL 40  
 ENTL 50  
 ENTL 60  
 ENTL 70  
 ENTL 80  
 ENTL 90  
 ENTL 100  
 ENTL 110  
 ENTL 120  
 ENTL 130  
 ENTL 140  
 ENTL 150  
 ENTL 160  
 ENTL 170  
 ENTL 180  
 ENTL 190  
 ENTL 200  
 ENTL 210  
 ENTL 220  
 ENTL 230  
 ENTL 240  
 ENTL 250  
 ENTL 260  
 ENTL 270  
 ENTL 280  
 ENTL 290  
 ENTL 300





```

SUBROUTINE LHR(T,X2,LH)
*****
*
*   UPDATED 4/15/78
*   LHR - LATENT HEAT ROUTINE
*
*****
*   ROUTINE IS CALLED BY *LHR(T,X2,LH)* WHERE T-TEMP.(K), X2-MOLE FR.
*   OF SO2 (T AND X2 ARE SPECIFIED BY THE CALLING PROG.), LH-LATENT
*   HEAT(KJ/KMOLE) TO BE CALCULATED.
*   BASIC DATA WERE TAKEN FROM NICKLESS. LATENT HEATS AS FUNCTION OF
*   TEMP. ARE CALCULATED ACCORDING TO PERRY'S CHEM. ENG. H.B., 5TH. ED.
*   (1973), PG. 3-239, EQ. 3-53. THE EXPONENT WAS TAKEN AS 0.545 (RATHER
*   THEN 0.38), WHICH RESULTED FROM CALCS. FOR BOTH SO2 AND SO3 FROM
*   ACTUAL REPORTED DATA OF LH(T) GIVEN BY EITHER NICKLESS OR BY
*   LANGE'S H.B. OF CHEMISTRY ED. J.A. DEAN, MGH 1973.
*   THE LH FOR THE MIXTURE IS CALCULATED ACCORDING TO PERRY'S EQ. 3-57
*   (PG. 3-239),  $LH=LH2*X2+LH3*X3$ . FINAL RESULTS CONVERTED INTO KJ/MOL
*   DATA USED -
*       SO2 TC=430K, TB=26JK, LH(263)=6.00KCAL/MOLE
*       SO3 TC=491K, TB=319K, LH(318)=9.75KCAL/MOLE
*
*NOMENCLATURE=
*   LH      OVERALL LATENT HEAT (KJ/KMOL)
*   LH2     LATENT HEAT OF SO2 AT GIVEN T
*   LH3     LATENT HEAT OF SO3 AT GIVEN T
*   T       TEMP. OF STREAM FOR WHICH LH IS CALC.
*   X2      MOLE FRACTION OF SO2 IN STREAM
*   X3      MOLE FRACTION OF SO3 IN STREAM
*****
REAL LH,LH2,LH3
X3=1.-X2
IF(T-430.) 1,2,2
2 IF(T-491.) 5,6,6
5 LH2=0.
GO TO 7
1 LH2=6.0*((430.-T)/167. )**0.545
7 LH3=9.75*((491.-T)/173. )**0.545
LH=4186.8*(LH2*X2+LH3*X3)
GO TO 4
6 LH=0.
PRINT 3,T
3 FORMAT(/3X,*LHR ROUTINE HAS BEEN CALLED TO CALC. LH FOR MIX. ABOVE
1 THE CRITICAL PT. SET LH=0. T=*,F7.2)
4 RETURN
END

```

```

SUBROUTINE VKCR(P,T,K2,K3)
*****
*
*   UPDATED 4/15/78
*   VKCR - VOLATILITY K CONSTANT ROUTINE
*
*****
*   ROUTINE IS CALLED BY *CALL VKCR(P,T,K2,K3)* WHERE P IS TOTAL
*   PRESSURE AND T IS TEMPERATURE. BOTH T AND P ARE SPECIFIED BY THE
*   CALLING PROGRAM. K2 AND K3 ARE THE VOLATILITY K CONSTANTS OF SO2
*   AND SO3 RESPECTIVELY WHICH ARE CALCULATED BY THE ROUTINE.
*   IT IS ASSUMED THAT SO2 AND SO3 FORM IDEAL SYSTEM, I.E. THE COMPONENTS
*   OF THE MIXTURE OBEY RAULT'S AND DALTON'S LAWS=
*    $PI = P \cdot YI = PSI \cdot XI$ 
*    $KI = YI / XI = PSI / P$ 
*   WHERE-
*   I   ONE OF THE MIXTURE COMPONENTS (I=2 FOR SO2, I=3 FOR SO3)
*   KI  VOLATILITY CONSTANT OF I
*   P   TOTAL SYSTEM PRESSURE
*   PI  PARTIAL PRESSURE OF COMPONENT I IN GAS
*   PSI VAPOR PRESSURE OF PURE LIQUID I
*   T   TEMPERATURE
*   XI  MOLE FRACTION OF I IN LIQUID
*   YI  MOLE FRACTION OF I IN GAS
*   PROGRAM USES E2 AND E3 AS INTERMEDIATE VARIABLES FOR THE EXPONENTS
*   OF 10 IN CALCULATING PS2 AND PS3 RESPECTIVELY.
*****
*   NOMENCLATURE
*   E2   EXPONENT POWER FOR ESTIMATING PS2
*   E3   EXPONENT POWER FOR ESTIMATING PS3
*   K2   VOLATILITY CONSTANT OF SO2
*   K3   VOLATILITY CONSTANT OF SO3
*   P    TOTAL SYSTEM PRESSURE
*   PS2  VAPOR PRESSURE OF PURE LIQ. SO2
*   PS3  VAPOR PRESSURE OF PURE LIQ. SO3
*   T    STREAM TEMP.
*****
*   DATA REFERENCE=
*   G.NICKLESS, INORGANIC SULFUR CHEMISTRY, ELSEVIER - 1968
*   PG.373 FOR SO2, PG.392 FOR SO3
*   PROGRAM ASSUMES THAT T IS IN (K) AND P IN (BAR).
*   SEE BPTR SUBROUTINE FOR DETAILS.
*****
REAL K2,K3
E2=12.0754-1867.52/T-0.015865*T+0.000015574*T**2
PS2=10.**E2*1.0133/76.
K2=PS2/P
E3=4.2719-945.78/(T-23.)
PS3=10.**E3*1.0133
K3=PS3/P
RETURN
END

```

```

SUBROUTINE BPTR(P,X2,TT)
*****BPTR 10
*
*
*   UPDATED 4/15/78
*   BPTR - BUBBLE POINT TEMPERATURE ROUTINE
*
*****BPTR 70
*
*   ROUTINE IS CALLED BY*CALL BPTR(P,X2,T)* WHERE P IS THE TOTAL
*   PRESSURE, X2 COMPOSITION OF THE SO2-SO3 LIQUIDE MIXTURE (X2=MOL
*   FR. OF SO2) AND T IS THE BOILLING PT. OF THE MIXTURE (BUBBLE PT.)*BPTR 100
*   VAPOR PRESSURE CORRELATIONS WERE TAKEN FROM G.NICKLESS,INORGANIC*BPTR 120
*   SULFUR CHEMISTRY,ELSEVIER-1968, P-373 FOR SO2,P-392 FOR SO3.
*   THE ACTUAL NUMERICAL VALUES OF THE ROUTINE PARAMETERS ARE MODIFIED*BPTR 140
*   TO ACCEPT TEMP. IN (K) AND P IN (BAR).
*   ROUTINE ASSUMES IDEAL SYSTEM= TOTAL VAPOR P = PSO2+PSO3 WHERE
*   PSOI=PS(T,I)*XI WHERE I=SO2,SO3. PS(T,I)=SATURATION VAP. PRESSURE*BPTR 170
*   OF COMPONENT I AT TEMP. T.
*****BPTR 190
*
*   LOGIC FLOW -
*   FIRST GUESS FOR T IS DONE BY SELECTING THE PROPER RANGE ACCORDING*BPTR 210
*   TO THE PRESSURE P(BAR), I.E. I=1 FOR P BETWEEN 0 AND 10 (0,10)
*   I=2 FOR P=(10,20),I=3 FOR P=(20,30),I=4 FOR P=(30,40),I=5 FOR P
*   OVER 40BAR. PROGRAM IS ESSENTIALLY LIMITED TO P=50BAR.
*FIRST GUESS FOR BUBBLE POINT (BP) IS TAKEN TO BE EQ. TO TI OF THE
*PARTICULAR RANGE. NEWTON RAPHSON SCHEME IS USED FOR CONVERGENCE.
*****BPTR 270
*
*   NOTATIONS -
*   A   CONST. PARAMETER IN VAP. PRESS. POLINOMINAL EQ.
*   B   CONST. PARAMETER IN VAP. PRESS. POLINOMINAL EQ.
*   C   CONST. PARAMETER IN VAP. PRESS. POLINOMINAL EQ.
*   C2  FACTOR TO CONVERT VAPOR PRESSURE INTO BARS
*   C3  FACTOR TO CONVERT VAPOR PRESSURE INTO BARS
*   D   CONST.PARAMETER IN VAP.PRESSURE POLINOMINAL EQ.
*   DPT DENOMINATOR IN LAST EQ. FOR DT
*   DP2 CONTRIBUTION OF SO2 TO THE CALCULATED DPT
*   DP3 CONTRIBUTION OF SO2 TO THE CALCULATED DPT
*   DT DIFFERENTIAL TEMP. CHANGE IN T SEARCHING LOOP
*   E   CONST.PARAMETER IN VAP.PRESSURE POLINOMINAL EQ.
*   EX2 EXPONENT OF 10 IN SO2 VAP.PRESSURE EQUATION
*   EX3 EXPONENT OF 10 IN SO3 VAP.PRESSURE EQUATION
*   G   CONST.PARAMETER IN VAP.PRESSURE POLINOMINAL EQ.
*   H   CONST.PARAMETER IN VAP.PRESSURE POLINOMINAL EQ.
*   I   DO LOOP INDEX I=1,M
*   J   NO. OF THE PRESSURE RANGE WITHIN T IS SEARCHED FOR
*   M   MAX. PERMISSABLE ITERATIONS IN DO LOOP
*   P   TOTAL PRESSURE GIVEN BY THE CALLING PROGRAM
*   PP2 SATURATED VAPOR PRESSURE OF SO2 AT TEMP T (EQUILIBRIUM)
*   PP3 SATURATED VAPOR PRESSURE OF SO3 AT TEMP T (EQUIL.)
*   PT  TOTAL PRESSURE CALC. BY THE ROUTINE
*   T   CALC. TEMP (K)
*   TENLN NATURAL LOG OF 10.

```



## APPENDIX C. (Continued)

SAMPLE PRINTOUT OF RESULTS

The following is a sample printout of the calculations at the base case conditions. To simplify the presentation, some parts were rearranged and repetitive printings of iterated calculations were omitted. The order of the printed results is preserved, however. Brief notes of explanation are also attached.

The program first prints the input data.

```

-----
MEBP PROGRAM
INPUT DATA
-----
NON-CHANGING DATA?P(1),P(5),P(21),T24,T27  11.000  40.000  11.000  573.000  693.000
-----
FIRST APPROX?T(1),X2(1),F(5),      X2(5),X2(18)  364.000  -.047  5.800  .020  .010
-----
SPECIFICATION? DT56,TWMAX,TMIN,PRSO2,XD,
  140.000  1153.000  333.000  .980  .990
-----
TOLERANCES? EPSF5,EPST5?      .0500  .5000
-----
GENERAL? N= 45  NDP= 30  NH=18
INCREMENTS OF STUDIED PARAMS. TWMAX,DT056,TMIN? 20.0  1  25.0  1  10.0  1
INCREMENTS OF STUDIED PARAMS. DELP, NDP?      5.0  1
-----

```

The program next enters the HTS - LTS loop. The printout is rather lengthy; only the last iteration is attached.

---

HTS ROUTINE

---

CONVERGENCE ON F(5) AND T(5)? DF5= .3366E-01 DT5= .6220E+01 HTS ROUTINE

---

CONVERGENCE ON F(5) AND T(5)? DF5= -.3055E-02 DT5= .2339E-03 HTS ROUTINE

---

CLR ROUTINE

---

INPUTS? NI= 6 NG=14 NL=16 T(OUT)= 333.00

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RESULTS OF CLR ROUTINE

SN	F	X1	X2	X3	T	H
6	.6484E+01	.1499E+00	.3247E+00	.5254E+00	.1147E+04	.5028E+05
14	.1124E+01	.8649E+00	.1010E+00	.3412E-01	.3330E+03	.1101E+04
16	.5360E+01	.	.3717E+00	.6283E+00	.3330E+03	.2967E+05

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CONDENSER LOAD? CL= .4838E+06

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CTR ROUTINE

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INPUTS? NI= 7 NG= 8 NL= 9 CL= .9198E+05

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RESULTS OF CTR ROUTINE

SN	F	X1	X2	X3	T	H
7	.6484E+01	.1499E+00	.3247E+00	.5254E+00	.5928E+03	.1524E+05
8	.5066E+01	.1919E+00	.3552E+00	.4529E+00	.4176E+03	.5548E+04
9	.1418E+01	.	.2157E+00	.7843E+00	.4176E+03	.1501E+05

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CONVERGENCE ACCURACY? CL= .9198E+05 COMPARE TO CCL= .9200E+05

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CLR ROUTINE

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INPUTS? NI= 8 NG=10 NL=11 T(OUT)= 393.37

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RESULTS OF CLR ROUTINE

SN	F	X1	X2	X3	T	H

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8	.5066E+01	.1919E+00	.3552E+00	.4529E+00	.4176E+03	.5548E+04
10	.2338E+01	.4166E+00	.3639E+00	.2194E+00	.3934E+03	.3809E+04
11	.2728E+01		.3477E+00	.6523E+00	.3934E+03	.1848E+05

CONDENSER LOAD? CL= .6961E+05

CLR ROUTINE  
 INPUTS? NI=10 NG=12 NL=13 T(OUT)= 343.00

RESULTS OF CLR ROUTINE

SN	F	X1	X2	X3	T	H
10	.2338E+01	.4166E+00	.3639E+00	.2194E+00	.3934E+03	.3809E+04
12	.1267E+01	.7691E+00	.1966E+00	.3422E-01	.3430E+03	.1471E+04
13	.1072E+01		.5617E+00	.4383E+00	.3430E+03	.2424E+05

CONDENSER LOAD? CL= .3302E+05

CLR ROUTINE  
 INPUTS? NI=12 NG=14 NL=15 T(OUT)= 333.00

RESULTS OF CLR ROUTINE

SN	F	X1	X2	X3	T	H
12	.1267E+01	.7691E+00	.1966E+00	.3422E-01	.3430E+03	.1470E+04
14	.1210E+01	.8052E+00	.1755E+00	.1922E-01	.3330E+03	.1118E+04
15	.5678E-01		.6461E+00	.3539E+00	.3330E+03	.2425E+05

CONDENSER LOAD? CL= .1886E+04

DISTILLATION COLUMN

FEED ENTERS BETWEEN PLATES? 10 AND 11

CTR ROUTINE  
 INPUTS? NI= 8 NG=10 NL=11 CL= .9269E+05

RESULTS OF CTR ROUTINE

SN	F	X1	X2	X3	T	H
8	.5066E+01	.1919E+00	.3552E+00	.4529E+00	.4176E+03	.5548E+04
10	.1738E+01	.5594E+00	.2988E+00	.1418E+00	.3785E+03	.2974E+04
11	.3328E+01		.3847E+00	.6153E+00	.3785E+03	.2096E+05

CONVERGENCE ACCURACY? CL= .9269E+05 COMPARE TO CCL= .9269E+05

CLR ROUTINE  
 INPUTS? NI=10 NG=12 NL=13 T(OUT)= 343.00

RESULTS OF CLR ROUTINE

SN	F	X1	X2	X3	T	H
10	.1738E+01	.5594E+00	.2988E+00	.1418E+00	.3785E+03	.2974E+04

12	.1267E+01	.7675E+00	.1988E+00	.3375E-01	.3430E+03	.1470E+04
13	.4713E+00		.5677E+00	.4323E+00	.3430E+03	.2412E+05

CONDENSER LOAD? CL= .1469E+05

## CLR ROUTINE

INPUTS? NI=12 NG=14 NL=15 T(OUT)= 333.0

## RESULTS OF CLR ROUTINE

SN	F	X1	X2	X3	T	H
12	.1267E+01	.7675E+00	.1988E+00	.3375E-01	.3430E+03	.1470E+04
14	.1209E+01	.8039E+00	.1773E+00	.1887E-01	.3330E+03	.1118E+04
15	.5732E-01		.6525E+00	.3475E+00	.3330E+03	.2412E+05

CONDENSER LOAD? CL= .1893E+04

OVERALL MAT. BAL. RESULTS IN X2(2) OF? .0321 COMPARE TO ASSUMED? .0327

END OF HTS RTN.

## LTS ROUTINE

## CTR ROUTINE

INPUTS? NI=28 NG=29 NL=43 CL= .2701E+05

CCL WAS CALLED TO CALC. FOR NONCONDENSIBLE MIXTURE. LOAD CALC. ON BASIS OF GAS ENTHALPY CHANGE ONLY. T(J)= 400.85 CL= .2701E+05

## RESULTS OF CTR ROUTINE

SN	F	X1	X2	X3	T	H
28	.1066E+01	.7629E-02	.6606E-01	.9263E+00	.7771E+03	.3095E+05
29	.1066E+01	.7629E-02	.6606E-01	.9263E+00	.4008E+03	.5618E+04
43	0.	0.	0.	0.	.4008E+03	

CONVERGENCE ACCURACY? CL= .2701E+05 COMPARE TO CCL= .2701E+05

## CTR ROUTINE

INPUTS? NI=37 NG=41 NL=42 CL= .4950E+04

CCL WAS CALLED TO CALC. FOR NONCONDENSIBLE MIXTURE. LOAD CALC. ON BASIS OF GAS ENTHALPY CHANGE ONLY. T(J)= 400.85 CL= .4950E+04

## RESULTS OF CTR ROUTINE

SN	F	X1	X2	X3	T	H
37	.1954E+00	.7629E-02	.6606E-01	.9263E+00	.7771E+03	.3095E+05
41	.1954E+00	.7629E-02	.6606E-01	.9263E+00	.4008E+03	.5618E+04
42	0.	0.	0.	0.	.4008E+03	

CONVERGENCE ACCURACY? CL= .4950E+04 COMPARE TO CCL= .4950E+04

## CTR ROUTINE

INPUTS? NI=38 NG=29 NL=43 CL= .2206E+05



CCL WAS CALLED TO CALC. FOR NONCONDENSIBLE MIXTURE. LOAD CALC. ON BASIS  
OF GAS ENTHALPY CHANGE ONLY. T(J)= 400.85 CL= .2206E+05

RESULTS OF CTR		ROUTINE				
SN	F	X1	X2	X3	T	H
38	.8709E+00	.7629E-02	.6606E-01	.9263E+00	.7771E+03	.3095E+05
29	.8709E+00	.7629E-02	.6606E-01	.9263E+00	.4008E+03	.5618E+04
43	0.	.	.	.	.4008E+03	.

CONVERGENCE ACCURACY? CL= .2206E+05 COMPARE TO CCL= .2206E+05

## CTR ROUTINE

INPUTS? NI=39 NG=30 NL=31 CL= .1805E+05

RESULTS OF CTR		ROUTINE				
SN	F	X1	X2	X3	T	H
39	.1066E+01	.7629E-02	.6606E-01	.9263E+00	.4008E+03	.5618E+04
30	.5781E+00	.1492E-01	.9468E-01	.8904E+00	.3820E+03	.4475E+04
31	.4882E+000.	.	.3120E-01	.9688E+00	.3820E+03-	.2657E+05

CONVERGENCE ACCURACY? CL= .1805E+05 COMPARE TO CCL= .1638E+05

## CLR ROUTINE

INPUTS? NI=30 NG=32 NL=33 T(OUT)= 343.00

RESULTS OF CLR		ROUTINE				
SN	F	X1	X2	X3	T	H
30	.5781E+00	.1492E-01	.9468E-01	.8904E+00	.3820E+03	.4475E+04
32	.1027E-01	.6219E+00	.1213E+00	.2568E+00	.3430E+03	.1665E+04
33	.5678E+000.	.	.9529E-01	.9047E+00	.3430E+03-	.3327E+05

CONDENSER LOAD? CL= .2146E+05

## CLR ROUTINE

INPUTS? NI=32 NG=34 NL=35 T(OUT)= 333.00

RESULTS OF CLR		ROUTINE				
SN	F	X1	X2	X3	T	H
32	.1027E-01	.6219E+00	.1213E+00	.2568E+00	.3430E+03	.1665E+04
34	.9050E-02	.7056E+00	.1211E+00	.1733E+00	.3330E+03	.1220E+04
35	.1219E-020.	.	.1226E+00	.8774E+00	.3330E+03-	.3460E+05

CONDENSER LOAD? CL= .4822E+02

END OF LTS RTN.

CALC. ARE REPEATED IF ANY OF THE FOLLOWING CONDS. IS NOT SATISFIED?

IF(ABS(2.0F(36)-F(1))-0.015)	F(36)= .10572E+01	F(1)= .21118E+01
IF(ABS(X2(1)-X2(36))-0.008)	X(36)= .65726E-01	X(1)= .65986E-01
IF(ABS(T(1)-T(36))-1.0)	T(36)= .36169E+03	T(1)= .36154E+03

Program then prints the High Temperature Reactor results. The terms used in the heading are defined below.

- NOS - number of the section
- L - length down the reactor (m)
- TW - outside wall temperature of tube ( $^{\circ}\text{K}$ )
- TS - inside wall temperature of tube ( $^{\circ}\text{K}$ )
- TB - bulk temperature of stream ( $^{\circ}\text{K}$ )
- Q - total heat absorbed up to this section
- QR - heat absorbed due to reaction up to this section
- QS - sensible heat absorbed up to this section
- C - actual conversion of  $\text{SO}_3$  up to this section
- $\text{YSO}_3$  - mole fraction  $\text{SO}_3$
- $\text{YSO}_2$  - mole fraction  $\text{SO}_2$
- $\text{YO}_2$  - mole fraction  $\text{O}_2$

The routine then prints the equilibrium conversion at the conditions of the catalyzed wall of each section.

PARAMETERS STUDIED? TWMAX=1153.0 TMIN=333.0 DTD56=140.0 PHTS=40.0

HIGH TEMP REACTOR DESIGN-COMPUTATION RESULTS

NOS	L	TW	TS	TB	Q	QR	QS	C	Y-S03	Y-S02	Y-02
1	.20	1061.7	1053.3	1006.8	.7314E+03	.4629E+03	.2693E+03	0.000	.967	.033	.000
2	.40	1063.9	1055.7	1010.5	.1450E+04	.9190E+03	.5313E+03	.006	.959	.038	.002
3	.60	1066.2	1058.1	1014.1	.2157E+04	.1371E+04	.7862E+03	.012	.95	.044	.006
4	.80	1068.3	1060.4	1017.7	.2852E+04	.1818E+04	.1034E+04	.018	.942	.050	.009
5	1.00	1070.5	1062.6	1021.1	.3535E+04	.2260E+04	.1275E+04	.024	.933	.055	.011
6	1.20	1072.5	1064.8	1024.5	.4206E+04	.2697E+04	.151E+04	.03	.925	.061	.014
7	1.40	1074.6	1067.0	1027.7	.4867E+04	.3129E+04	.1738E+04	.036	.917	.066	.017
8	1.60	1076.5	1069.1	1030.9	.5516E+04	.3556E+04	.1960E+04	.041	.909	.071	.02
9	1.80	1078.5	1071.1	1034.0	.6154E+04	.3978E+04	.2176E+04	.047	.901	.076	.022
10	2.00	1080.3	1073.1	1037.1	.6781E+04	.4395E+04	.2386E+04	.053	.893	.082	.025
11	2.20	1082.2	1075.1	1040.0	.7397E+04	.4807E+04	.2590E+04	.058	.886	.087	.027
12	2.40	1084.0	1077.0	1042.9	.8004E+04	.5215E+04	.2789E+04	.064	.878	.092	.03
13	2.60	1085.7	1078.9	1045.7	.8600E+04	.5618E+04	.2982E+04	.069	.871	.097	.035
14	2.80	1087.5	1080.7	1048.5	.9186E+04	.6016E+04	.3170E+04	.075	.864	.101	.035
15	3.00	1089.1	1082.5	1051.2	.9762E+04	.6409E+04	.3354E+04	.08	.856	.106	.037
16	3.20	1090.8	1084.3	1053.8	.1033E+05	.6797E+04	.3532E+04	.086	.849	.111	.040
17	3.40	1092.4	1086.0	1056.3	.1089E+05	.7181E+04	.3705E+04	.091	.842	.116	.042
18	3.60	1094.0	1087.7	1058.8	.1143E+05	.7560E+04	.3874E+04	.096	.835	.121	.044
19	3.80	1095.5	1089.3	1061.2	.1197E+05	.7935E+04	.4038E+04	.101	.829	.125	.047
20	4.00	1097.0	1090.9	1063.6	.1250E+05	.8304E+04	.4198E+04	.107	.822	.129	.049
21	4.20	1098.5	1092.5	1065.9	.1302E+05	.8670E+04	.4353E+04	.112	.815	.133	.05
22	4.40	1099.9	1094.0	1068.2	.1354E+05	.9030E+04	.4505E+04	.117	.809	.138	.051
23	4.60	1101.3	1095.5	1070.3	.1404E+05	.9387E+04	.4652E+04	.122	.802	.142	.055
24	4.80	1102.7	1097.0	1072.5	.1453E+05	.9738E+04	.4796E+04	.127	.796	.146	.058
25	5.00	1104.0	1098.4	1074.6	.1502E+05	.1009E+05	.4936E+04	.132	.79	.15	.06
26	5.20	1105.3	1099.9	1076.6	.1550E+05	.1043E+05	.5072E+04	.136	.784	.154	.063
27	5.40	1106.6	1101.2	1078.6	.1597E+05	.1077E+05	.5205E+04	.141	.778	.158	.064

28	5.60	1107.9	1102.6	1080.6	.1644E+05	.1110E+05	.5334E+04	.146	.772	.162	.066
29	5.80	1109.1	1103.9	1082.5	.1689E+05	.1143E+05	.5460E+04	.151	.766	.166	.068
30	6.00	1110.3	1105.2	1084.3	.1734E+05	.1176E+05	.5582E+04	.155	.760	.170	.071
31	6.20	1111.5	1106.5	1086.1	.1778E+05	.1208E+05	.5702E+04	.16	.754	.174	.072
32	6.40	1112.7	1107.7	1087.9	.1821E+05	.1240E+05	.5818E+04	.164	.749	.178	.074
33	6.60	1113.8	1108.9	1089.6	.1864E+05	.1271E+05	.5931E+04	.169	.743	.181	.076
34	6.80	1114.9	1110.1	1091.3	.1906E+05	.1302E+05	.6042E+04	.173	.738	.185	.077
35	7.00	1116.0	1111.3	1092.9	.1947E+05	.1332E+05	.6149E+04	.178	.732	.188	.079
36	7.20	1117.1	1112.4	1094.5	.1988E+05	.1363E+05	.6254E+04	.182	.727	.192	.081
37	7.40	1118.1	1113.5	1096.1	.2028E+05	.1392E+05	.6357E+04	.186	.722	.195	.083
38	7.60	1119.1	1114.6	1097.6	.2067E+05	.1422E+05	.6457E+04	.191	.717	.199	.084
39	7.80	1120.1	1115.7	1099.1	.2106E+05	.1451E+05	.6554E+04	.195	.712	.202	.086
40	8.00	1121.1	1116.7	1100.6	.2144E+05	.1479E+05	.6649E+04	.199	.707	.205	.088
41	8.20	1122.1	1117.8	1102.0	.2182E+05	.1507E+05	.6741E+04	.203	.702	.209	.089
42	8.40	1123.0	1118.8	1103.4	.2218E+05	.1535E+05	.6832E+04	.207	.697	.212	.091
43	8.60	1123.9	1119.7	1104.8	.2255E+05	.1563E+05	.6920E+04	.211	.692	.215	.093
44	8.80	1124.8	1120.7	1106.1	.2290E+05	.1590E+05	.7006E+04	.215	.688	.218	.094
45	9.00	1125.7	1121.7	1107.4	.2325E+05	.1616E+05	.7091E+04	.219	.683	.221	.096
46	9.20	1126.6	1122.6	1108.7	.2360E+05	.1643E+05	.7172E+04	.223	.679	.224	.097
47	9.40	1127.4	1123.5	1109.9	.2394E+05	.1669E+05	.7252E+04	.227	.674	.227	.099
48	9.60	1128.2	1124.4	1111.2	.2427E+05	.1694E+05	.7331E+04	.23	.670	.23	.10
49	9.80	1129.1	1125.3	1112.4	.2460E+05	.1720E+05	.7406E+04	.234	.665	.233	.102
50	10.00	1129.9	1126.1	1113.5	.2493E+05	.1745E+05	.7480E+04	.238	.661	.236	.103
51	10.20	1130.6	1127.0	1114.7	.2525E+05	.1769E+05	.7553E+04	.241	.657	.238	.105
52	10.40	1131.4	1127.8	1115.8	.2556E+05	.1794E+05	.7624E+04	.245	.653	.241	.106
53	10.60	1132.2	1128.6	1116.9	.2587E+05	.1817E+05	.7693E+04	.249	.649	.244	.107
54	10.80	1132.9	1129.4	1117.9	.2617E+05	.1841E+05	.7761E+04	.252	.645	.246	.109
55	11.00	1133.6	1130.2	1119.0	.2647E+05	.1864E+05	.7827E+04	.256	.641	.249	.11
56	11.20	1134.3	1131.0	1120.0	.2677E+05	.1887E+05	.7891E+04	.259	.637	.252	.111
57	11.40	1135.0	1131.7	1121.0	.2705E+05	.1910E+05	.7955E+04	.262	.633	.254	.113
58	11.60	1135.7	1132.4	1122.0	.2734E+05	.1932E+05	.8016E+04	.266	.629	.257	.114

59	11.80	1136.4	1133.2	1122.9	.2762E+05	.1954E+05	.8077E+04	.269	.626	.259	.115
60	12.00	1137.1	1133.9	1123.9	.2790E+05	.1976E+05	.8136E+04	.272	.622	.262	.116
61	12.20	1137.7	1134.6	1124.8	.2817E+05	.1998E+05	.8193E+04	.276	.618	.264	.118
62	12.40	1138.3	1135.3	1125.7	.2844E+05	.2019E+05	.8250E+04	.279	.615	.266	.119
63	12.60	1138.9	1135.9	1126.6	.2870E+05	.2040E+05	.8305E+04	.282	.611	.269	.120
64	12.80	1139.6	1136.6	1127.5	.2896E+05	.2060E+05	.8359E+04	.285	.608	.271	.121
65	13.00	1140.2	1137.2	1128.3	.2922E+05	.2080E+05	.8411E+04	.288	.605	.273	.122
66	13.20	1140.7	1137.9	1129.1	.2947E+05	.2100E+05	.8463E+04	.291	.601	.275	.123
67	13.40	1141.3	1138.5	1129.9	.2972E+05	.2120E+05	.8514E+04	.294	.598	.278	.124
68	13.60	1141.9	1139.1	1130.7	.2996E+05	.2140E+05	.8563E+04	.297	.595	.280	.126
69	13.80	1142.4	1139.7	1131.5	.3020E+05	.2159E+05	.8611E+04	.300	.591	.282	.127
70	14.00	1143.0	1140.3	1132.3	.3044E+05	.2178E+05	.8659E+04	.303	.588	.284	.128
71	14.20	1143.5	1140.9	1133.0	.3067E+05	.2196E+05	.8705E+04	.306	.585	.286	.129
72	14.40	1144.1	1141.4	1133.8	.3090E+05	.2215E+05	.8750E+04	.308	.582	.288	.130
73	14.60	1144.6	1142.0	1134.5	.3112E+05	.2233E+05	.8795E+04	.311	.579	.290	.131
74	14.80	1145.1	1142.5	1135.2	.3135E+05	.2251E+05	.8838E+04	.314	.576	.292	.132
75	15.00	1145.6	1143.1	1135.9	.3156E+05	.2268E+05	.8881E+04	.317	.573	.294	.133
76	15.20	1146.1	1143.6	1136.6	.3178E+05	.2286E+05	.8922E+04	.319	.570	.296	.134
77	15.40	1146.6	1144.1	1137.2	.3199E+05	.2303E+05	.8963E+04	.322	.568	.298	.135
78	15.60	1147.0	1144.6	1137.9	.3220E+05	.2320E+05	.9003E+04	.324	.565	.299	.136
79	15.80	1147.5	1145.1	1138.5	.3241E+05	.2336E+05	.9042E+04	.327	.562	.301	.137
80	16.00	1148.0	1145.6	1139.1	.3261E+05	.2353E+05	.9081E+04	.329	.559	.303	.137
81	16.20	1148.4	1146.1	1139.8	.3281E+05	.2369E+05	.9118E+04	.332	.557	.305	.138
82	16.40	1148.8	1146.6	1140.4	.3300E+05	.2385E+05	.9155E+04	.334	.554	.307	.139
83	16.60	1149.3	1147.1	1141.0	.3320E+05	.2401E+05	.9191E+04	.337	.552	.308	.140
84	16.80	1149.7	1147.5	1141.5	.3339E+05	.2416E+05	.9227E+04	.339	.549	.310	.141
85	17.00	1150.1	1148.0	1142.1	.3358E+05	.2432E+05	.9261E+04	.342	.547	.312	.142
86	17.20	1150.5	1148.4	1142.7	.3376E+05	.2447E+05	.9295E+04	.344	.544	.313	.143
87	17.40	1150.9	1148.8	1143.2	.3394E+05	.2461E+05	.9329E+04	.346	.542	.315	.143
88	17.60	1151.3	1149.3	1143.8	.3412E+05	.2476E+05	.9362E+04	.349	.539	.316	.144
89	17.80	1151.7	1149.7	1144.3	.3430E+05	.2491E+05	.9394E+04	.351	.537	.318	.145

90	18.00	1152.1	1150.1	1144.8	.3447E+05	.2505E+05	.9425E+04	.353	.535	.321	.146
91	18.20	1152.5	1150.5	1145.3	.3464E+05	.2519E+05	.9456E+04	.355	.532	.321	.147
92	18.40	1152.9	1150.9	1145.8	.3481E+05	.2533E+05	.9486E+04	.357	.530	.323	.147
93	18.60	1153.2	1151.3	1146.3	.3498E+05	.2546E+05	.9516E+04	.359	.528	.324	.148
94	18.80	1153.6	1151.7	1146.8	.3514E+05	.2560E+05	.9545E+04	.362	.526	.325	.149
95	19.00	1153.9	1152.1	1147.3	.3530E+05	.2573E+05	.9573E+04	.364	.524	.327	.150
96	19.00	0.0	0.0	1147.7	0.	0.	0.	.364	.521	.328	.150

THERMAL POWER ABSORBED BY GAS- .2299E+03MW-THERMAL) SOURCE TEMP.=1176.4(K) DIFF=-.2897E-02MW

Equilibrium conversion at  
wall conditions in each section  
of the High Temperature Reactor  
L - length down the reactor, m  
EC - equilibrium conversion

L	EC	L	EC
.20	.2370	4.80	.3650
.40	.2912	5.00	.3676
.60	.2953	5.20	.3702
.80	.2993	5.40	.3727
1.00	.3032	5.60	.3752
1.20	.3071	5.80	.3777
1.40	.3109	6.00	.3800
1.60	.3146	6.20	.3824
1.80	.3183	6.40	.3846
2.00	.3218	6.60	.3869
2.20	.3253	6.80	.3891
2.40	.3288	7.00	.3912
2.60	.3321	7.20	.3933
2.80	.3354	7.40	.3954
3.00	.3387	7.60	.3974
3.20	.3418	7.80	.3994
3.40	.3450	8.00	.4013
3.60	.3480	8.20	.4032
3.80	.3510	8.40	.4051
4.00	.3539	8.60	.4069
4.20	.3568	8.80	.4087
4.40	.3596	9.00	.4105
4.60	.3623	9.20	.4122
		9.40	.4139
		9.60	.4155
		9.80	.4172
		10.00	.4188
		10.20	.4203
		10.40	.4219
		10.60	.4234
		10.80	.4248

L	EC	L	EC
11.00	.4263	15.20	.4511
11.20	.4277	15.40	.4520
11.40	.4291	15.60	.4530
11.60	.4304	15.80	.4539
11.80	.4318	16.00	.4548
12.00	.4331	16.20	.4557
12.20	.4344	16.40	.4566
12.40	.4356	16.60	.4574
12.60	.4369	16.80	.4583
12.80	.4381	17.00	.4591
13.00	.4393	17.20	.4599
13.20	.4405	17.40	.4607
13.40	.4416	17.60	.4615
13.60	.4427	17.80	.4623
13.80	.4439	18.00	.4630
14.00	.4449	18.20	.4638
14.20	.4460	18.40	.4645
14.40	.4471	18.60	.4652
14.60	.4481	18.80	.4660
14.80	.4491	19.00	.4667
15.00	.4501	19.00	.4667

HTR RETURNS WITH?				F(6)	T(6)	P(6)
				6,482	1147,729	40,000
X1(6)	X2(6)	X3(6)	FC	TWM		
.150	.327	.524	.364	1153,929		



The program then prints the steam turbine results. All flows in the scheme of Fig. 3.5. are shown for four modes of operation: normal daytime; normal night (large turbine, no actual power generation); normal night (small turbine); and seasonal storage (nighttime at normal daytime output).

TMIR(K) = 333. H12(BTU/LB) = 1069. P12(PSIA) = 2.331

DAY-TIME OPERATION.

WATER TO BOILER	334895.9
SEAL LEAK - 1	393.7
SEAL LEAK - 2	114.4
SEAL LEAK - 3	3383.3
SEAL LEAK - 4	1381.5
SEAL LEAK - 5	468.8
HP - EXTRACTION	32227.9
REHEATER FLOW	296916.4
IP-FLOW AT VALVE	297319.1
IP TOTAL FLOW	300693.5
SEAL LEAK - 6	517.3
IP EXTRACTION	10524.7
VAP.+DIST. STEAM	255833.4
LP TOTAL FLOW	83818.0
TOTAL CONDENSATE	1558.2

DIRECT STEAM GEN. TO STORAGE RATIO=1.0500

POWER GENERATED AT HP TURBINE=	23.61
POWER GENERATED AT LP TURBINE=	7.28
TOTAL POWER GENERATED	= 30.89

NIGHT-TIME OPERATION

LARGE TURBINE AT 3.5P.C. OF DAY-TIME FLOW

R = .2466E-02 R1 = .1748E-01

WATER TO BOILER	5852.0
SEAL LEAK - 1	6.9
SEAL LEAK - 2	2.0
SEAL LEAK - 3	59.1
SEAL LEAK - 4	22.7
SEAL LEAK - 5	8.2
HP - EXTRACTION	563.3
REHEATER FLOW	5189.7
IP-FLOW AT VALVE	5196.6
IP TOTAL FLOW	5255.8
SEAL LEAK - 6	9.0
IP EXTRACTION	641.2
VAP.+DIST. STEAM	0.0
LP TOTAL FLOW	4605.5
TOTAL CONDENSATE	4624.7

POWER GENERATED AT HP TURBINE=	.41
POWER GENERATED AT LP TURBINE=	.40
TOTAL POWER GENERATED	= .81

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 POWER RATE AT SMALL TURBINE DURING 16 HRS AT NIGHT.
 

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 R= .4584E-01    R1= .3249E+00
 

---

WATER TO BOILER	108791.2
SEAL LEAK - 1	127.9
SEAL LEAK - 2	37.2
SEAL LEAK - 3	1099.4
SEAL LEAK - 4	422.9
SEAL LEAK - 5	152.3
HP - EXTRACTION	10472.1
REHEATER FLOW	96479.4
IP-FLOW AT VALVE	96607.4
IP TOTAL FLOW	97706.7
SEAL LEAK - 6	168.1
IP EXTRACTION	11920.2
VAP.+DIST. STEAM	0.0
LP TOTAL FLOW	85618.5
TOTAL CONDENSATE	85976.1

---

 POWER GENERATED AT HP TURBINE= 7.67
 

---

 POWER GENERATED AT LP TURBINE= 7.43
 

---

 TOTAL POWER GENERATED = 15.11
 

---

 TURBINE AT SEASONAL STORAGE OP. CONDITIONS
 

---

 DISCHARGE AT FULL LOAD 8.245HRS. NEEDS 1.941 DAYS OF STORAGE TO  
 RUN 16 HRS AT FULL LOAD
 

---

 R= .9374E-01    R1= .6645E+00
 

---

WATER TO BOILER	222476.9
SEAL LEAK - 1	261.6
SEAL LEAK - 2	76.0
SEAL LEAK - 3	2248.2
SEAL LEAK - 4	864.8
SEAL LEAK - 5	311.5
HP - EXTRACTION	21415.2
REHEATER FLOW	197299.5
IP-FLOW AT VALVE	197561.1
IP TOTAL FLOW	199809.3
SEAL LEAK - 6	343.7
IP EXTRACTION	24376.6
VAP.+DIST. STEAM	0.0
LP TOTAL FLOW	175089.0
TOTAL CONDENSATE	175820.2

---

 POWER GENERATED AT HP TURBINE= 15.69
 

---

 POWER GENERATED AT LP TURBINE= 15.20
 

---

 TOTAL POWER GENERATED = 30.89
 

---

The results of the distillation column are then printed.

```

DISTILLATION COLUMN
INPUT DATA
STREAM      F          T          P          H          C          Q
FEED        2.573    391.083    40.000-18776.293    .359
BOTTOM
DISTILLATE          .990    45212.440
P=10.78  PRSD2= .980  N= 30
  
```

RESULTS OF THE DISTILLATION COLUMN

FLASH RESULTS? IFF= 363.68 FL= .7022E+04 FX2= .2833 FV= .2240E+04 FY2= .5959

HEAT INPUT TO REBOILER IS NOT ENOUGH. QR-MIN SHOULD BE OVER .4521E+02 MW  
DIST. COL. IS CALCUL. FOR QR-MIN

FEED ENTERS BETWEEN PLATES? 1 AND 11

OUTPUT?

REBOILER? B= .1659E+01 XB= .011 TB=383.4 QR= .4521E+05

FEED? F= .2573E+01 XF= .359 TF=391.1

CONDENSER? D= .9141E+00 XD= .990 TD=333.0 QC= .5703E+05

PLATES CONDITIONS

J	T	L	X	HL	V	Y	HV
1	383.4	.5972E+04	.011	-.2663E+05	.5199E+04	.036	.4680E+04
2	382.4	.1117E+05	.022	-.2664E+05	.5220E+04	.070	.4557E+04
3	381.5	.1119E+05	.039	-.2664E+05	.5243E+04	.118	.4429E+04
4	379.2	.1121E+05	.061	-.2663E+05	.5285E+04	.178	.4260E+04
5	376.9	.1126E+05	.090	-.2660E+05	.5362E+04	.250	.4060E+04
6	374.5	.1132E+05	.124	-.2648E+05	.5447E+04	.330	.3848E+04
7	371.7	.1142E+05	.163	-.2636E+05	.5551E+04	.408	.3625E+04
8	369.0	.1152E+05	.202	-.2619E+05	.5663E+04	.477	.3422E+04
9	366.6	.1163E+05	.238	-.2600E+05	.5765E+04	.534	.3254E+04
10	364.7	.1174E+05	.268	-.2583E+05	.5892E+04	.582	.3123E+04
11	362.6	.4801E+04	.302	-.2561E+05	.8225E+04	.620	.2986E+04
12	358.5	.4934E+04	.373	-.2506E+05	.8561E+04	.699	.2728E+04
13	351.1	.5276E+04	.517	-.2368E+05	.9257E+04	.816	.2306E+04
14	342.3	.5959E+04	.720	-.2126E+05	.1009E+05	.920	.1858E+04
15	336.3	.6803E+04	.886	-.1899E+05	.1065E+05	.974	.1578E+04
16	333.7	.7364E+04	.966	-.1781E+05	.1089E+05	.993	.1460E+04

NO. OF PLATES M=16 DEVIATION FROM XD= .0035 DEVIATION FROM V= -.6403E-09

Finally, the program prints in Tables 1 and 2 following values of the process stream flows, compositions, temperatures, pressures, and enthalpies. The details of the low temperature (nighttime) reactors are then printed. The last two tables are then repeated for flows corresponding to the daytime rate of power generation, in this case 30.89 MW<sub>e</sub>.

PARAMETERS STUDIED? TWMAX=1153.0 TMIN=333.0 DTD56=140.0 PHTS=40.0

TABLE-1, MATERIAL AND ENERGY DATA FOR THE DAYTIME HIGH TEMPERATURE SIDE STORAGE SYSTEM

STREAM NO.	COMPOSITION (MOL PR.)			TEMP. (K)	PRESSURE (BAR)	FLOW (KMOL/S)	ENTHALPY (KJ/KMOL)
	O2	SO2	SO3				
1	0.00	0.07	0.93	361.5	11.0	1.03	-30199.5
2	0.00	0.03	0.97	375.2	40.0	2.69	-28003.2
3	0.00	0.03	0.97	443.2	40.0	2.69	-11317.7
4	0.00	0.03	0.97	443.2	40.0	2.69	8262.8
5	0.00	0.03	0.97	1006.8	40.0	2.69	49476.3
6	0.15	0.33	0.52	1147.7	40.0	3.16	50278.0
7	0.15	0.32	0.53	592.8	40.0	3.16	15241.8
8	0.19	0.36	0.45	417.6	40.0	2.47	5547.8
9	0.00	0.22	0.78	417.6	40.0	0.69	-15004.1
10	0.56	0.30	0.14	378.5	40.0	0.85	2973.7
11	0.00	0.38	0.62	378.5	40.0	1.62	-20957.0
12	0.77	0.20	0.03	343.0	40.0	0.62	1470.1
13	0.00	0.57	0.43	343.0	40.0	0.23	-24124.9
14	0.80	0.18	0.02	333.0	40.0	0.59	1118.3
15	0.00	0.65	0.35	333.0	40.0	0.03	-24124.5
16	0.00	0.36	0.64	391.1	40.0	2.57	-18776.3
17	0.00	0.99	0.01	333.7	10.8	0.91	-17809.2
18	0.00	0.01	0.99	383.4	10.8	1.66	-26626.5

HEAT EXCHANGER LOAD (KW)?

C1L= 44865.855 VAP1L= 52650.271 HE1L=110819.380 RCL= 45212.440

BFWHL= 1558.230 TRIMMER= 6523.535 QRFS= 11259.464

SUMMARY OF EFFICIENCIES AT THE CHOSEN PARAMETERS

E1= 0.2631

E2= 0.5337

E3= 0.5789

TABLE-2, MATERIAL AND ENERGY BALANCES FOR THE NIGHT TIME OPERATION OF THE LOW TEMPERATURE SIDE

STREAM NO.	COMPOSITION (MOL PR.)			TEMP. (K)	PRESSURE (BAR)	FLOW (KMOL/S)	ENTHALPY (KJ/KMOL)
	O2	SO2	SO3				
21	0.00	.99	.01	333.7	11.0	.46	-17899.2
22	0.00	.99	.01	333.7	11.0	.46	1460.1
23	.80	.18	.02	333.0	40.0	.29	1118.3
24	.80	.18	.02	573.0	40.0	.29	9303.6
25	.01	.99	.01	333.7	11.0	.46	1457.8
26	.32	.67	.01	354.7	11.0	.76	2138.8
27	.32	.67	.01	693.0	11.0	.76	16365.5
28	.01	.07	.93	777.1	11.0	.52	30949.0
29	.01	.07	.93	400.8	11.0	.42	5618.3
30	.01	.09	.89	382.0	11.0	.28	4475.2
31	0.00	.03	.97	382.0	11.0	.24	-26570.8
32	.02	.11	.87	381.3	11.0	.22	4409.5
33	0.00	.04	.96	381.3	11.0	.06	-26609.4
34	.71	.11	.18	333.0	11.0	.01	1217.2
35	0.00	.11	.89	333.0	11.0	.21	-34816.7
36	0.00	.07	.93	361.7	11.0	.52	-30175.2
37	.01	.07	.93	777.1	11.0	.10	30949.0
38	.01	.07	.93	777.1	11.0	.42	30949.0
39	.01	.07	.93	400.8	11.0	.52	5618.3
40	.80	.18	.02	396.2	11.0	.29	3204.0
41	.01	.07	.93	400.8	11.0	.10	5618.3
42	0.00	0.00	0.00	400.8	0.0	0.00	0.0
43	0.00	0.00	0.00	400.8	0.0	0.00	0.0
44	0.00	0.00	0.00	0.0	0.0	0.00	0.0
45	0.00	0.00	0.00	0.0	0.0	0.00	0.0

HEAT EXCHANGERS LOAD (KW)? RECUP= 10761.049 VAP= 8806.663  
 BFW= 1831.551 TRIM= 8356.963 HE2= 2414.515

ENERGY PRODUCED AT NIGHT? QAAN= .4034E+05 GTW= .1799E+04(KW)

RECEIVER LOAD TQA= 112.2(MW-THRM)

## RESULTS OF THE LOW TEMP. REACTORS SYSTEM

NO.	O2	SO2	SO3	(K)	(BAR)	(KMOL/S)	(KJ/KMOL)
50	.32	.67	.01	693.0	11.0	.76	16365.5
51	.22	.48	.29	1150.3	11.0	.66	44834.6
52	.22	.48	.29	693.0	11.0	.66	18975.0
53	.13	.31	.55	1016.3	11.0	.60	42057.5
54	.13	.31	.55	693.0	11.0	.60	21362.6
55	.06	.17	.76	912.2	11.0	.55	38590.5
56	.06	.17	.76	693.0	11.0	.55	23324.3
57	.02	.09	.90	815.4	11.0	.53	33426.4
58	.02	.09	.90	752.3	11.0	.53	28798.2
59	.01	.07	.93	777.1	11.0	.52	30949.0
60	.01	.07	.93	777.1	11.0	.52	30949.0
Q 1	.1716E+05	Q 2 .1234E+05	Q 3 .8407E+04	Q 4 .2431E+04	Q 50.		
X	.367X	.418X	.489X	.531X	.233		
LTR CONVERSION. C = .932							

TABLE-2, MATERIAL AND ENERGY BALANCES FOR THE NIGHT TIME OPERATION OF THE LOW TEMPERATURE SIDE

STREAM NO.	COMPOSITION (MOL PR.)			TEMP. (K)	PRESSURE (BAR)	FLOW (KMOL/S)	ENTHALPY (KJ/KMOL)
	O2	SU2	SO3				
21	0.00	.99	.01	333.7	11.0	.89	-17809.2
22	0.00	.99	.01	333.7	11.0	.89	1460.1
23	.80	.18	.02	333.0	40.0	.57	1118.3
24	.80	.18	.02	573.0	40.0	.57	9303.6
25	.01	.99	.01	333.7	11.0	.99	1457.8
26	.32	.67	.01	354.7	11.0	1.47	2138.8
27	.32	.67	.01	693.0	11.0	1.47	16365.5
28	.01	.07	.93	777.1	11.0	1.01	30949.0
29	.01	.07	.93	400.8	11.0	.82	5618.3
30	.01	.09	.89	382.0	11.0	.55	4475.2
31	0.00	.03	.97	382.0	11.0	.46	-26570.8
32	.02	.11	.87	381.3	11.0	.42	4409.5
33	0.00	.04	.96	381.3	11.0	.12	-26609.4
34	.71	.11	.18	333.0	11.0	.01	1217.2
35	0.00	.11	.89	333.0	11.0	.41	-34816.7
36	0.00	.07	.93	361.7	11.0	1.00	-30175.2
37	.01	.07	.93	777.1	11.0	.18	30949.0
38	.01	.07	.93	777.1	11.0	.82	30949.0
39	.01	.07	.93	400.8	11.0	1.01	5618.3
40	.80	.18	.02	396.2	11.0	.57	3204.0
41	.01	.07	.93	400.8	11.0	.18	5618.3
42	0.00	0.00	0.00	400.8	0.0	0.00	0.0
43	0.00	0.00	0.00	400.8	0.0	0.00	0.0
44	0.00	0.00	0.00	0.0	0.0	0.00	0.0
45	0.00	0.00	0.00	0.0	0.0	0.00	0.0
HEAT EXCHANGERS LOAD (KW)?				RECUP= 20882.928	VAP= 17090.240		
BFW= 3554.315				TRIM= 16217.551	HE2= 4685.616		
ENERGY PRODUCED AT NIGHT? QAAN=				.7828E+05	GTW= .3492E+04(KW)		
RECEIVER LOAD TQA=				446.3(MW-THRM)			



TECHNICAL INFORMATION DEPARTMENT  
LAWRENCE BERKELEY LABORATORY  
UNIVERSITY OF CALIFORNIA  
BERKELEY, CALIFORNIA 94720