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A SOLAR - HEATED GAS-TURBINE PROCESS USING SULFUR
OXIDES FOR POWER PRODUCTION AND ENERGY STORAGE

George Kohler Tyson*, Scott Lynn, and Alan Foss

September 1979

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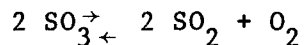
A SOLAR - HEATED GAS-TURBINE PROCESS
USING SULFUR OXIDES FOR POWER PRODUCTION
AND ENERGY STORAGE

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ABSTRACT

If any system of solar power generation is to provide a significant fraction of the power requirements of a community, some means of economical energy storage must be used. The purpose of this study was to develop and evaluate a process configuration using the heat of reaction of:



for energy storage. The forward reaction is endothermic and is used to absorb energy. The reverse reaction is exothermic and releases the energy that has been stored. This process uses the sulfur oxides directly in a gas turbine in a hybrid Brayton-Rankine cycle to produce electricity. Heat for the 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 provides the heat to drive the gas turbine.

In this report an efficient process configuration for this power cycle is proposed. Detailed material and energy balances are presented for a base case that represents a middle range of expected operating conditions. The sensitivity of this process to variations

in the key operating parameters was determined. Equipment sizes and costs were estimated for the base case to determine an approximate cost for the electricity produced by this process.

In the base case the solar receiver absorbs heat at a rate of 230 MW_t for a period of eight hours during the day. Daytime electricity generation is about 52.3 MW_e . Nighttime generation is about 19.0 MW_e for a period of 16 hours. The overall efficiency of converting heat into electricity is thus about 39%. The total capital cost for the base case is \$71.7 million, of which 69% is for the tower and heliostat field. The average cost of the electricity produced is estimated to be 7.7¢/ kW_e hr.

I. Introduction

If any system of solar power generation is to match effectively the power requirements of a community, some means of energy storage must be used. The use of sensible heat and latent heat in energy storage systems has been described previously.¹ The process described in this report utilizes the heat of the reversible reaction $\text{SO}_3 \rightleftharpoons \text{SO}_2 + 1/2 \text{O}_2$ to store thermal energy in a form useful for power generation.

In this process heat is absorbed in a central receiver surrounded by a mirror field. The receiver and mirror field used in this model are an adaptation of a design proposed by Boeing.² These mirrors track the sun and focus solar radiation onto the receiver during the day. The receiver reaches temperatures in excess of 900°C. A stream of liquid SO_3 is pumped from storage to a pressure of 40 bar and vaporized in a series of heat exchangers on its way to the receiver. Here, it absorbs more heat and is partially dissociated catalytically into SO_2 and O_2 . The hot stream is then expanded through a turbine to generate electricity, cooled, and separated into a liquid SO_2 stream and a gaseous O_2 stream that are sent to storage and an SO_3 -rich liquid that is recycled to the receiver.

Heat recovery is provided by essentially reversing the process during the night or during periods of cloud cover. The SO_2 and O_2 react catalytically and release the heat absorbed during the day. The hot gases, at 40 bar and 770°C, are expanded in a turbine to generate electricity. The resulting SO_3 is cooled and sent to storage to be reused during the day.

The power cycle outlined above is a novel combination of the Brayton and Rankine cycles. The use of liquids that are pumped to maximum system pressure and then vaporized, and the condensation and recycle of the SO_3 after expansion through the turbine, make the cycle similar to the Rankine cycle. The increase in the number of moles of gas that results from reaction at high temperature, and the recompression of part of the gas that has been expanded makes the cycle similar to the Brayton cycle. Because it is a true thermodynamic cycle, much better utilization is made of the high temperatures achieved from reaction than would be the case if the reactor effluent were used only as a heat-transfer medium. The cycle was first proposed by Dayan et al.³ This work is a continuation of their effort, in which a number of process modifications have been introduced and the capabilities and limitations of the process have been more clearly defined.

This process is also similar to another earlier work by Dayan et al.⁴ Dayan used a sulfur-oxide storage process integrated with a solar, steam-cycle power plant. In that work, steam was generated in the receiver to power a turbine during the day, while SO_3 reacted in a parallel set of tubes in the same receiver. The exothermic oxidation reaction supplied heat to the steam boiler at night. Dayan's results showed that the efficiency of converting heat into electricity was relatively low, about 26%, so that the cost of the power produced was high, about 11¢/kW hr.

The process reported here uses the SO_x stream from the receiver-reactor directly for power production to increase overall process efficiency. The high thermodynamic potential of the SO_x stream is utilized more fully by using the stream as the power fluid in the gas turbines.

One of the major components of this study has been the synthesis of an efficient configuration of gas turbines, compressors, and heat recovery systems. Evaluations of the expected energy recovery were made through heat and material balances for daytime and nighttime systems. The sensitivity of system energy efficiency was also studied over a range of process operating parameters. System costs were estimated to determine the cost of the electric power generated. No attempt was made, however, to search for a minimum-cost process; the state of the process development is still too rudimentary for that. It is possible, however, to make comparisons with the storage system of Dayan et al., and these are given in Chapter VIII.

The use of the heat of a chemical reaction to store energy has several advantages over the other methods of energy storage:

1. The quality of heat released can be high. Temperatures in excess of 1040 K (1400^oF) can be obtained in the discharge mode, making power generation feasible.

2. The storage volume required is relatively low, as two of the reactants, SO_2 and SO_3 , are stored as liquids. Oxygen storage is more difficult, as discussed in Chapter V.

3. There is flexibility in the duration of storage such as weekly or seasonal, in that the reactants are stored at ambient temperature without degradation of the stored energy. Energy loss to the environment during prolonged periods of storage is thus prevented. Storage capacity can therefore be built up during weekends, for gradual depletion during the week, for example.

The disadvantages of chemical energy storage arise primarily from the novelty of the concept. There is no existing technology that closely approximates the process proposed here, so that extensive developmental work would be required to demonstrate its technical feasibility.

II. Design Bases and Specifications

The process developed uses as a basis a solar receiver and mirror field designed by Boeing² to absorb 230 MW_t of heat. Minor modifications were made to this receiver design to allow for the chemical reaction that takes place in this process. Table 2.1 shows the values of other parameters taken for the base case.

The potential of this novel power cycle is shown by the results for the base case. The net electrical output is 52.3 MW_e for 8 hours during the day and 19.0 MW_e for 16 hours during the night. The overall system efficiency, defined as (net electrical output)/(total thermal input) is thus 39%. These results are discussed in detail in Chapter VI.

Many assumptions and simplifications were used in this work. Some of the major ones are:

1. Fluctuations in weather conditions were ignored. A constant solar input for 8 hours and a discharge period of 16 hours were assumed. This is fairly conservative, as near-peak solar input normally ranges from 8 to 14 hours per day. The effect of different periods of insolation on power costs is shown in Chapter VII.

2. A minimum system temperature of 40°C (104°F) was assumed for the base case. In reality this would vary with both the season and the time of day. The effect of changing this minimum temperature is discussed in Chapter VI.

3. A maximum tube-wall temperature in the receiver-reactor tubes of 880°C (1620°F) was assumed for the base case. Materials considerations put an upper limit on this temperature. The effect of varying this wall temperature is also discussed in Chapter VI.

Table 2.1 Parameter Values Set for the Base Case

Tower load (MW_t)	230
Hours of sunlight per day	8
Hours of nighttime power production	16
Maximum tube wall temp. (K)	1153
Minimum system temp. (K)	313
High pressure, daytime (bar)	40
Exhaust pressure, daytime (bar)	2.5
High pressure, nighttime (bar)	40
Exhaust pressure, nighttime (bar)	2
Turbine efficiency (%)	90
Compressor efficiency (%)	85

4. A minimum temperature approach at 10°C was used in all heat exchangers. This is a commonly accepted value for optimal design.

Materials problems will clearly be severe in this process, not only for the reactor tubes and connecting piping, but also for the turbine blades and housing. Hill⁵ made a literature search for suitable materials and concluded that Haynes 188 was the most promising of available alloys due to its corrosion resistance and extraordinary high-temperature strength.

The properties of Haynes 188, composed of 38% Co, 22% Cr, 22% Ni, and 3% Fe, are such that it would be expected to resist corrosion in this system to the extent that replacement would be made for structural reasons before any appreciable corrosion would result. This is the major advantage of this alloy. Experimental verification of the suitability of Haynes 188 has not yet been done and would be required as part of any future work on this project.

The requirements for the materials for the rest of the process are not nearly so stringent and present no unusual problems. For the heat exchangers and nighttime reactors 316 stainless steel will be adequate. Carbon steel will be sufficient for the storage vessels.

III. Daytime Process

A block flow diagram of the daytime process is shown in Fig. 3.1. Conditions of the streams are presented in Table 3.1.

The liquid SO_3 is pumped through a series of heat exchangers (COND-A, COND-B, VAP-1, VAP-2), where it is vaporized and slightly superheated. The stream then enters the first section of the tower (HE-1), where it is further heated. It then enters the reactor portion of the tower where the SO_3 partially dissociates into SO_2 and O_2 while absorbing more sensible heat. At this point the stream is at the highest temperature of any point in the system. It is thus most suitable for expansion, and flows next through a gas turbine to generate electricity. After passing through the turbine, the exhaust stream preheats the feed to the receiver (VAP-2, COND-B) and is then cooled to the minimum system temperature in TRIM-1.

The condensate that forms at this point is insufficiently enriched in SO_2 to justify storing, so it is combined with the fresh SO_3 feed (stream 1) and recycled to the receiver. This recycle increases the amount of SO_2 circulating through the system but saves greatly on the amount of SO_3 feed required by reducing the amount of SO_3 in the SO_2 that is stored.

The remaining vapor (stream 11) is then recompressed. The hot stream is partially cooled by preheating the tower feed (VAP-1, COND-A), then is cooled to the minimum temperature in TRIM-2. The condensing stream (17) is the SO_2 product and is stored as a liquid. The remaining vapor (16) is mostly O_2 and must be stored as a gas.

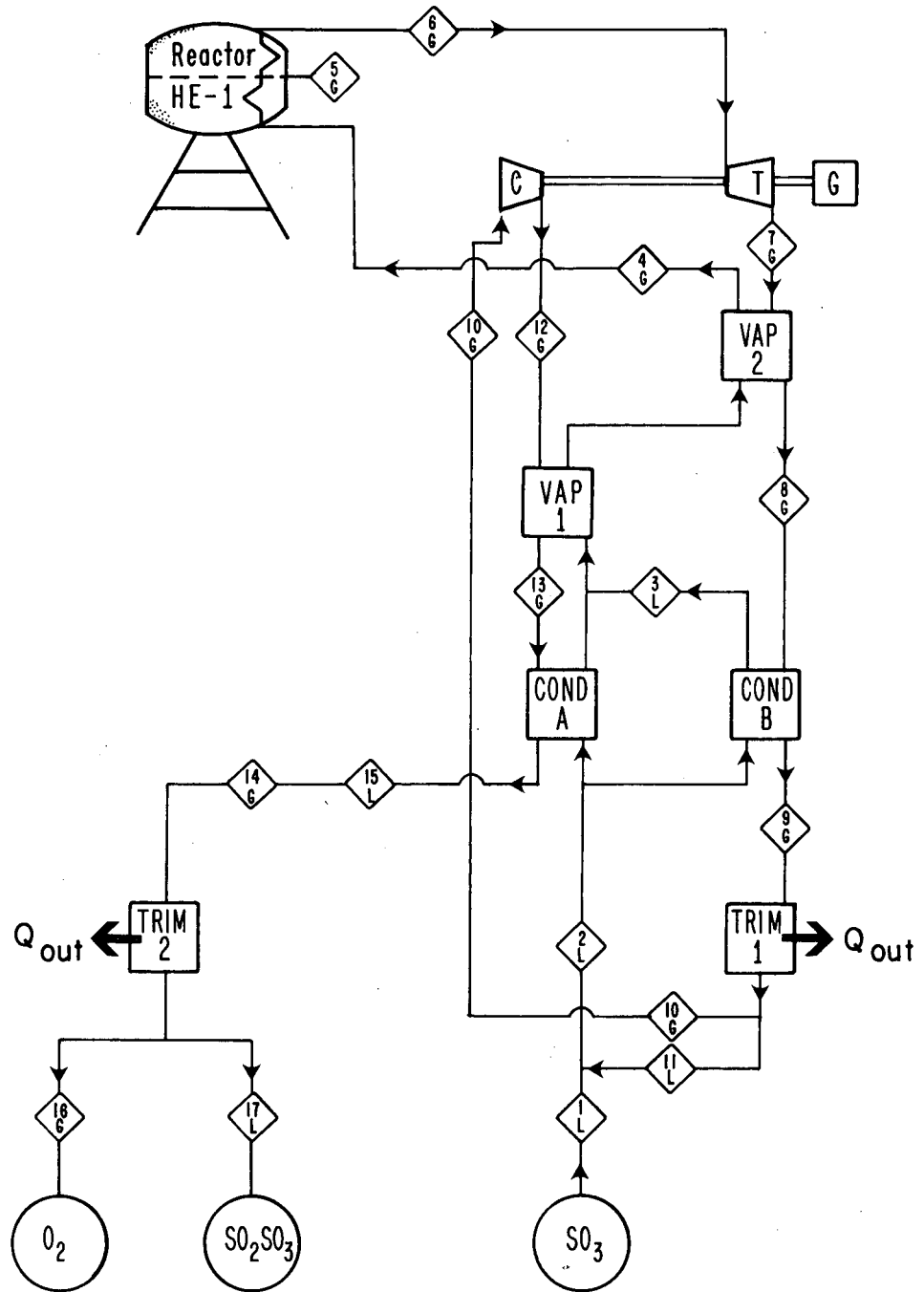


Fig. 3.1 Block Flow Diagram of the Daytime (Charge) Process

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Table 3.1 Stream Conditions and Heat Exchanger Duties for the HTS (Daytime).

Process

Stream No.	State	Flow (kmole/sec)	Pres. (bar)	Temp. (°K)	Ethalpy (MJ/kmole)	Concentration (Mole Fraction)		
						O ₂	SO ₂	SO ₃
1	l	1.74	40.0	313	-39.4	.00	.06	.94
2	l	3.33	40.0	313	-38.2	.00	.12	.88
3	l	3.33	40.0	436	-11.7	.00	.12	.88
4	g	3.33	40.0	555	15.1	.00	.12	.88
5	g	3.33	40.0	1007	48.1	.00	.12	.88
6	g	3.80	40.0	1147	50.5	.12	.36	.52
7	g	3.80	2.5	841	30.3	.12	.36	.52
8	g	3.80	2.5	446	7.2	.12	.36	.52
9	g	3.80	2.5	323	1.1	.12	.36	.52
10	g	2.22	2.5	313	0.6	.21	.48	.31
11	l	1.59	2.5	313	-36.8	.00	.19	.81
12	g	2.22	40.0	549	11.6	.21	.19	.60
13	g	2.22	40.0	536	11.0	.21	.19	.60
14	g	0.58	40.0	333	1.1	.82	.16	.02
15	l	1.63	40.0	333	-25.4	.00	.59	.41
16	g	0.53	40.0	313	0.5	.90	.09	.01
17	l	1.69	40.0	313	-28.4	.00	.60	.40

Heat Exchanger Loads (MW_t)

COND-A	65.2
COND-B	23.1
VAP-1	1.4
VAP-2	87.7
TRIM-1	61.2
TRIM-2	6.8
Receiver	
HE-1	109.6
Reactor	120.4

The heat and material balances presented in Tables 3.1 and 4.1 (which appears in Chapters IV) were obtained from a computer model of the daytime and nighttime processes. In this model the following assumptions and simplifications were made:

1. Pressure drops were neglected in the computer model of this system. Actual equipment design, as described in Chapter VII, is partially based on minimizing these pressure drops.

2. Raoult's law was used for liquid mixtures. This simplified the calculations without introducing major errors. Experimental verification of this may be advisable.

3. The SO_2 , SO_3 , and O_2 were assumed to behave as ideal gases. This is a good approximation due to their high critical pressures.

4. Ideal gas heat capacities were used to determine stream enthalpies. Pressure effects on these were thus neglected. This is a good estimate at temperatures well above the boiling point, where it is most important.

Several components of this system warrant further discussion:

1. The Receiver

The receiver is based on a design proposed by Boeing² and was discussed in an earlier study of a sulfur oxide energy storage process by Dayan et al.⁴ A more detailed description of its construction and operation is given in their paper.

The receiver in this system contains a series of tubes in a brick-lined cavity situated on top of a 300 meter tower. A field of

mirrors concentrates sunlight on this receiver to produce the high temperatures required for reaction and power generation.

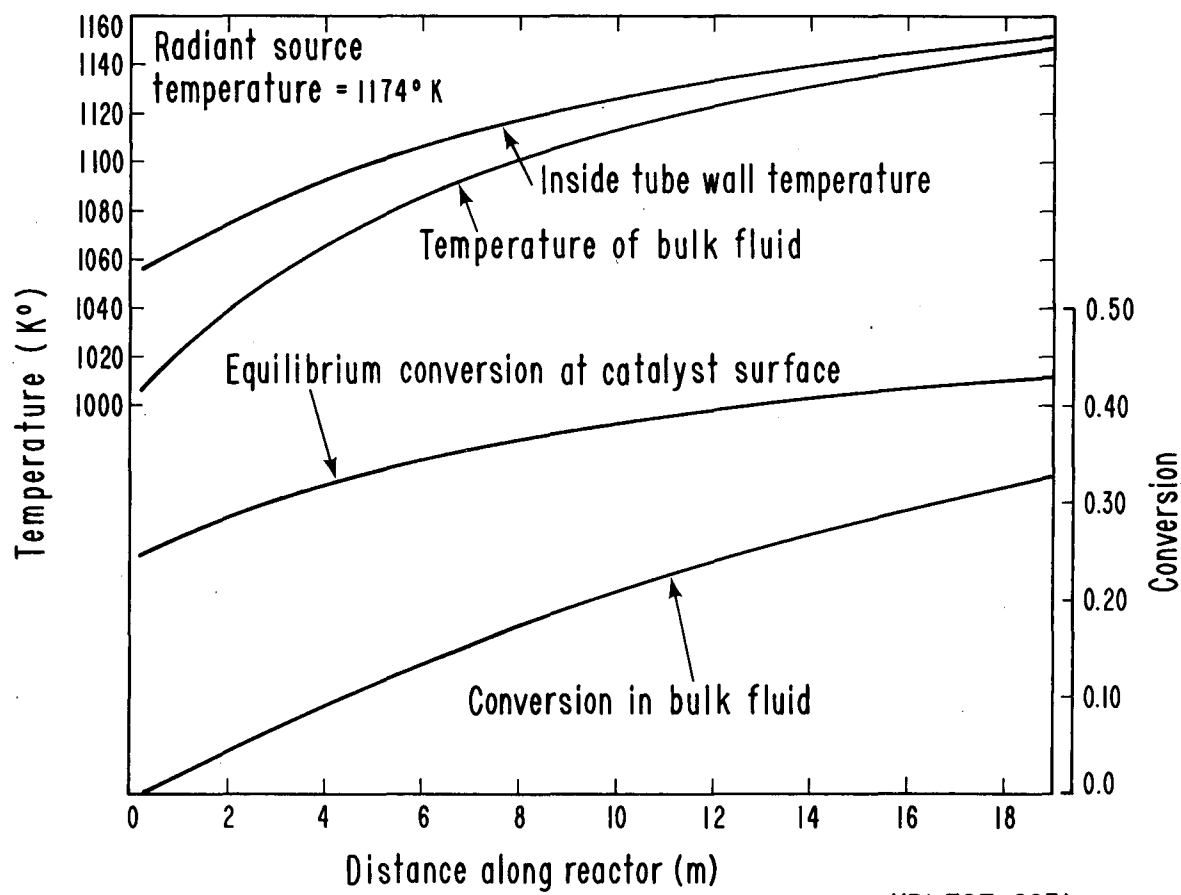
For this process, the receiver absorbs 230 MW_t of thermal energy. It contains 5600 tubes, each 9.5 m long. These tubes are constructed of Haynes 188, an alloy with high strength and good corrosion resistance. In this system the receiver comprises two sections.

a. Section HE-1 contains 1420 tubes in which the incoming stream is heated to a suitable reaction temperature (1000 K). The stream absorbs 109.6 MW_t in this part of the receiver. There is no catalyst in this section and the reaction does not proceed.

b. The reactor section heats the stream further while partially dissociating the SO_3 . The inside of the tubes is coated with a commercial Fe_2O_3 catalyst. Temperature and conversion profiles in the reactor are shown in Fig. 3.2 to demonstrate the approach to equilibrium.

This section absorbs 120.4 MW_t and contains the remaining 4180 tubes. These are arranged such that the stream passes through two banks of tubes, forming an equivalent of 2090 tubes, each 19 m long. This improves mass transfer by increasing the Reynolds number, and equilibrium is more closely approached.

The behavior of the reactor section was simulated with a one-dimensional plug-flow model that is more completely discussed by Dayan et al.⁴ A uniform radiative temperature of 1174 K was calculated and is seen by all tubes in both sections. At these high



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Fig. 3.2 Temperature and Conversion Profiles in the Receiver-Reactor

temperatures, reaction kinetics were assumed to be very fast. Mass-transfer resistances, however, were found to be significant and are dominated by the rate of diffusion of SO_2 from the catalytic reaction zone into the bulk fluid.

The catalyst used in this model is Fe_2O_3 , chosen for its effectiveness at high temperatures, its low cost, and the practicality of coating it on the inside of the reactor tubes. The suitability of this catalyst for this reaction was demonstrated by Hill⁵.

2. Turbine

In this process a hot (1140 K) mixture of SO_3 , SO_2 , and O_2 expands adiabatically in a turbine from 40 bar to 2.5 bar to generate electricity. Materials problems are expected to be most severe here. Further investigation of the applicability of Haynes 188 is a necessary next step.

The turbine produces 77 MW_e of electricity during the day and 21 MW_e during the night in the base case. To avoid the problem of running a turbine at much less than its design flow, a two-turbine arrangement seems advisable. During the day, two turbines could be run, one 60 MW_e (A), the other 20 MW_e (B). At night A could be allowed to cool while B continues at its design flow and maintains high efficiency. Variations of this idea may be even more practical, with 4 or 5 20 MW_e turbines, for example, to permit better maintenance and replacement.

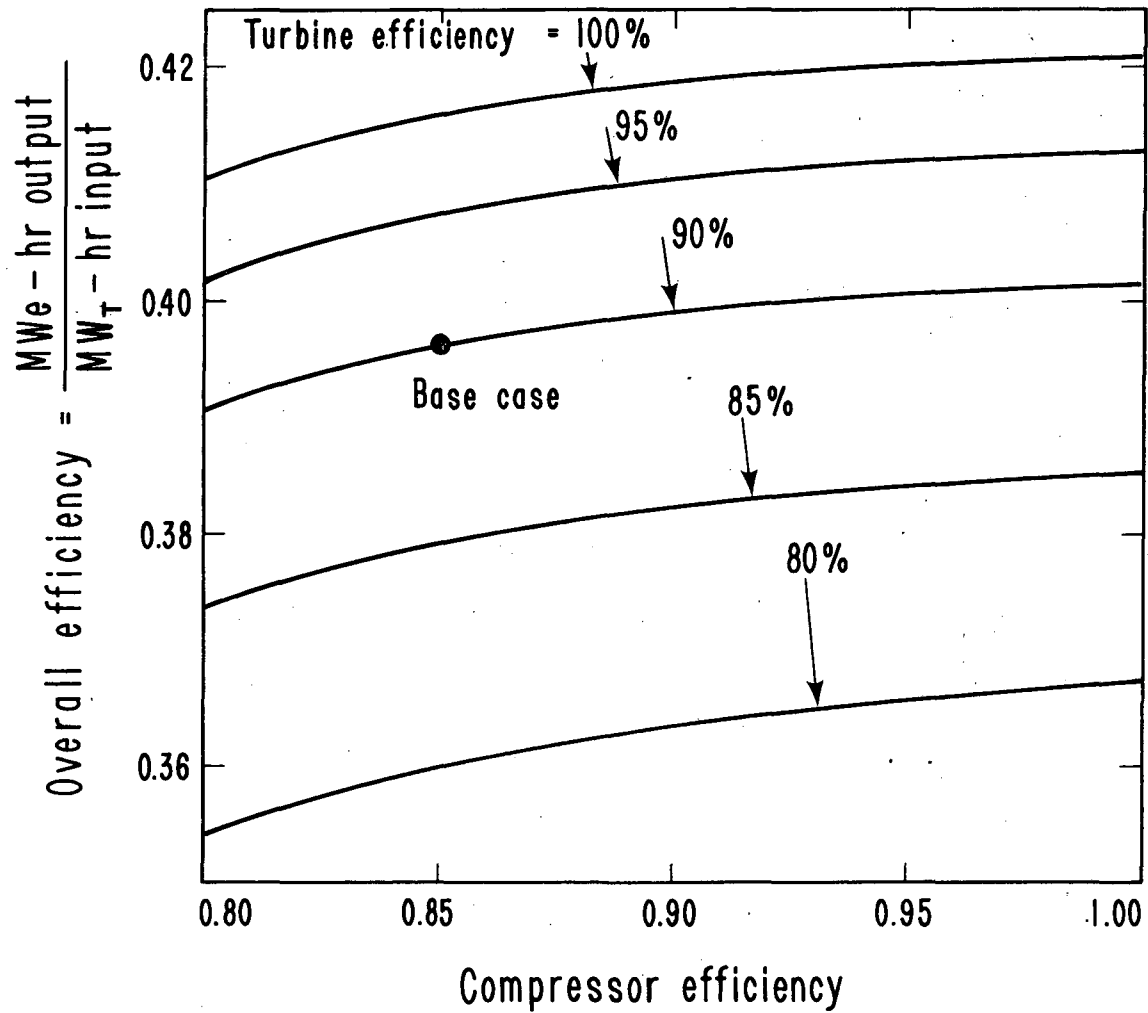
To alleviate any problems with the operation of an initially cold turbine, a bleed from the operating turbine could be used to heat the cold turbine(s) gradually prior to sunrise. The effect on overall system performance would not be great.

3. Compressor

The uncondensed vapor from TRIM-1 is compressed adiabatically from 2.5 bar to 40 bar using power directly from the turbine. The materials problems with this compressor would be less severe than those of the turbine because of the lower temperatures reached.

An alternative to a single compressor is to have several compressors, with interstage cooling and condensation. The cooling would be provided by the SO_3 feed stream from storage. Interstage cooling would reduce the total amount of gas to be compressed because of the condensing of the SO_2 and SO_3 . On the other hand, a lower quality of heat in the outlet stream from the compressor would result, reducing the amount of preheating of stream 2 that would be accomplished. Optimization would be required to determine the best strategy.

For the base case, a turbine efficiency of 90% and a compressor efficiency of 85% were assumed. Rather than performing a detailed estimate of expected efficiencies, the effects of varying turbine and compressor efficiencies on the overall process efficiency were calculated and are shown in Fig. 3.3. The process is clearly more sensitive to turbine efficiencies due to their greater load.



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Fig. 3.3 Effect of Turbine and Compressor Efficiencies on Overall Efficiency

4. Heat Exchangers

The condensers and vaporizers are arranged to yield the best possible use of the heat available. The tower feed is heated by successively hotter streams to maximize the thermodynamic efficiency. In the two condensers (COND-A, COND-B) the tower feed is first heated to its bubble point (435 K). Any remaining heat in the compressor outlet (12) is used in VAP-1 to begin the vaporization of stream (3). Finally, stream (7) completes the vaporization and slightly superheats the tower feed (4). Stream (7) has the highest quality suitable for preheating heat and, therefore, heats the feed stream last.

This arrangement of heat exchange eliminates the need for an external heat supply to achieve vaporization of the tower feed. An additional heat exchanger might be included in the flowsheet ahead of the tower to supply heat during start-up, but it would not be needed for steady state operation.

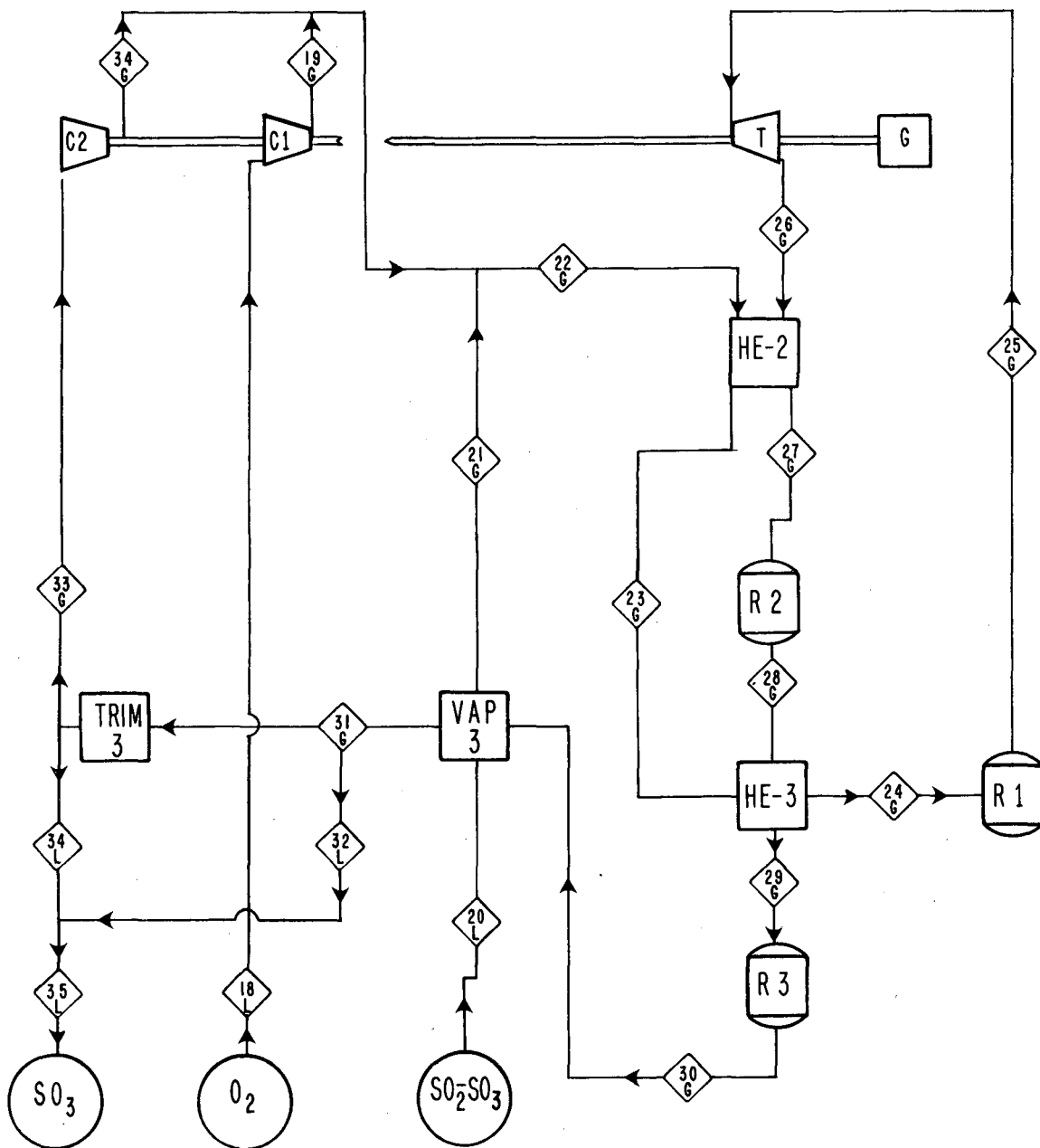
Both trimmers (TRIM-1, TRIM-2) cool the streams to the minimum system temperature, T_{\min} , which was assumed to be 10°C higher than the ambient. Since this system will most likely be located in a desert region, dry cooling is proposed. Water may be unavailable or prohibitively expensive. The effect of the value chosen for T_{\min} on the overall system efficiency is discussed in Chapter VI.

IV. Nighttime Process

When storage is discharged, the SO_2 and O_2 recombine to form SO_3 and the heat of the reaction is used to heat the gas stream that drives the turbine to generate power. A block flow diagram of the nighttime process is shown in Fig. 4.1 and conditions of the streams are presented in Table 4.1.

The SO_2 stream (20) is pumped from storage and is vaporized by a hot exhaust stream. The O_2 stream from storage (18) is compressed to maintain a pressure of 40 bar as the storage chamber is emptied. The two streams (19 and 21) are mixed and heated in HE-2 to the V_2O_5 catalyst ignition temperature of 420°C . Stream (23) is then reacted in R-1 to 99% of equilibrium. At this point, the reactor outlet stream (25) is at the highest temperature ever reached in the discharge process, and thus is most suitable for expansion.

After expansion in the gas turbine, stream (26) is cooled to the lowest catalyst reaction ignition temperature (420°C) in HE-2. Stream (27) then passes into R-2, where additional SO_2 and O_2 react, is cooled in HE-3, and then flows to R-3 where the reaction is brought closer to completion. The hot stream is then cooled in the SO_2 vaporizer (VAP-3) and finally cooled to the minimum system temperature in TRIM-3. The stream of condensate (35), mostly SO_3 with some SO_2 , is sent to storage to be used during the day. The uncondensed gas (33), mostly unreacted O_2 and SO_2 , is compressed back to 40 bar and is recycled through the system.



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Fig. 4.1 Block Flow Diagram of the Nighttime (Discharge) Process

Table 4.1 Stream Conditions and Heat Exchanger Duties for the LTS (Nighttime) Process.

Stream No.	State	Flow (kmole/sec)	Pres. (bar)	Temp. (K)	Enthalpy (MJ/kmole)	Composition (Mole Fraction)		
						O ₂	SO ₂	SO ₃
18	g	0.27	40.0	313	0.4	.90	.09	.01
19	g	0.27	40.0	388	2.8	.90	.09	.01
20	l	0.85	40.0	313	-28.4	.00	.60	.40
21	g	0.85	40.0	532	11.8	.00	.60	.40
22	g	1.24	40.0	516	10.0	.23	.44	.32
23	g	1.24	40.0	562	12.4	.23	.45	.32
24	g	1.24	40.0	693	19.1	.23	.45	.32
25	g	1.10	40.0	1045	45.1	.13	.25	.62
26	g	1.10	2.0	751	25.5	.13	.25	.62
27	g	1.10	2.0	693	21.8	.13	.25	.62
28	g	1.04	2.0	852	34.1	.08	.15	.77
29	g	1.04	2.0	693	31.2	.08	.15	.77
30	g	1.00	2.0	791	35.1	.05	.08	.87
31	g	1.00	2.0	328	1.5	.05	.08	.87
32	l	0.00	2.0	328	-37.7	.00	.02	.98
33	g	0.13	2.0	313	0.6	.37	.18	.45
34	g	0.13	40.0	571	12.9	.37	.18	.45
35	l	0.87	2.0	313	-39.5	.00	.06	.94
36	l	0.87	8.0	313	-39.5	.00	.06	.94

Heat Exchanger Loads (MW_t)

VAP-3	33.9
HE-2	4.0
HE-3	11.3
TRIM-3	35.6

A slight excess of SO_2 is maintained in the feed to the reactor series to minimize the amount of O_2 circulating through the system. Oxygen recycle requires compression, which reduces the net work obtained from the turbines.

Again, several components of the discharge process warrant further discussion.

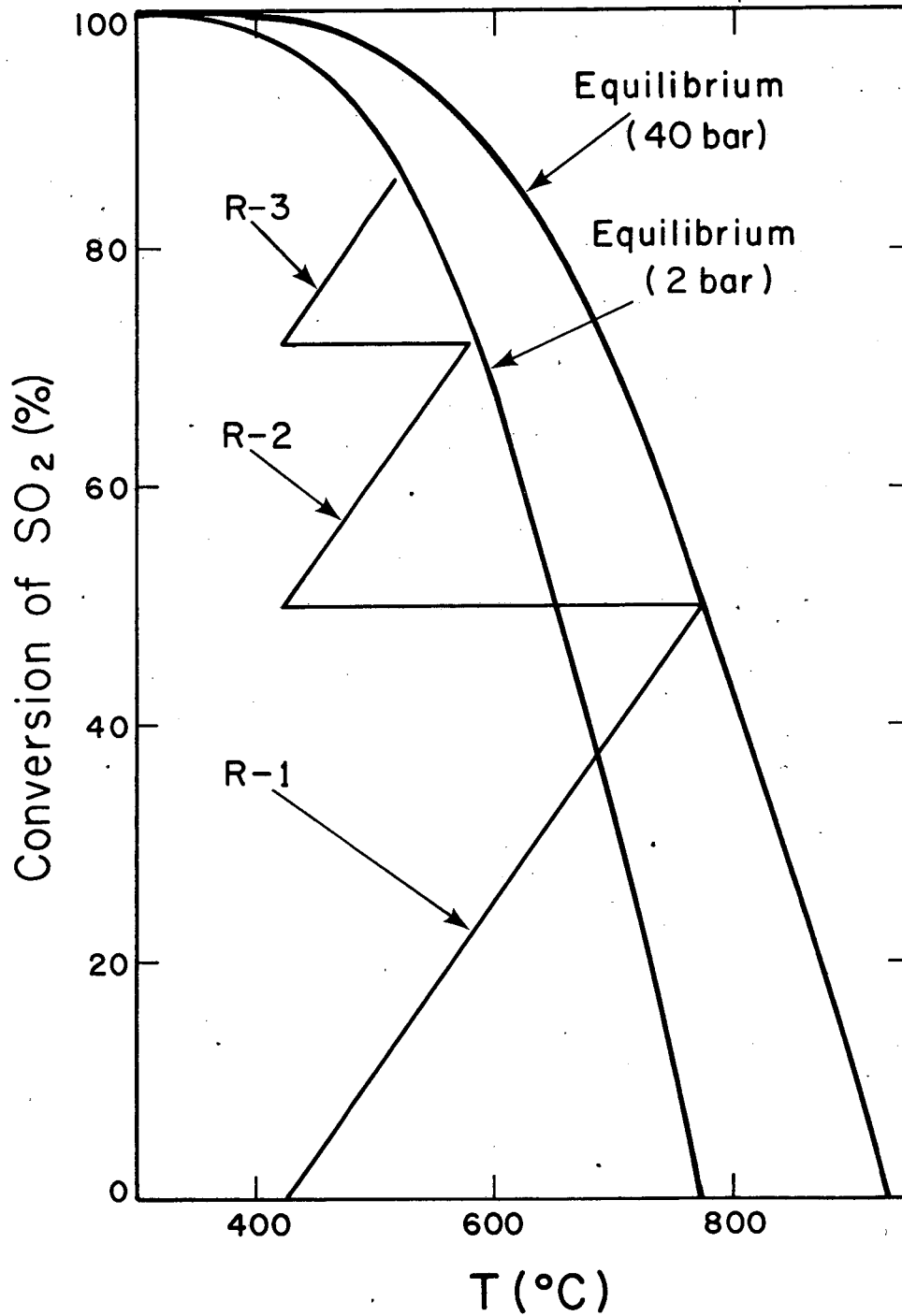
1. Low-Temperature Reactors

The reactors used in this model are those proposed by Hill.⁵ His results and conclusions are summarized below.

The oxidation of SO_2 is a common industrial reaction in the production of H_2SO_4 . Since the object here is to reach the high temperatures that are avoided in the sulfuric acid process, the approach is somewhat different. A bed of commercial supported- V_2O_5 catalyst is contacted with an entering stream at 420°C (693 K). The reaction proceeds adiabatically until the stream reaches 600°C . Above this temperature (with a 20°C safety margin) V_2O_5 is increasingly volatile and loses its effectiveness.

The reaction is then finished with a different catalyst. Platinized asbestos, proposed by Hill, has good activity above 550°C and is able to withstand temperatures in excess of 880°C . This lower range of activity allows a safety margin should the inlet temperature to the bed drop.

In this calculation the approach to equilibrium was set at 99% in each reactor. Conversion and temperature changes effected in the three reactors are shown in Fig. 4.2. This figure shows that the



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Fig. 4.2 Conversion and Temperature Changes in the Low Temperature Reactors

total conversion of the inlet SO_2 is 86%. Only R-1 requires platinized asbestos, as the temperature will not exceed 600°C in the other two.

Figure 4.3 shows the relative sizes of the three reactors. R-1 is very small because the high fractional conversion that can be achieved in this stage leads to a high temperature so that the reaction proceeds quickly. R-2 and R-3 become successively larger because lower fractional conversions of SO_2 occur, leading to lower temperatures and slower reaction rates.

At one stage of the process development, an additional reactor was added to note its effect on the overall process. The additional SO_2 reacted and heat liberated were so small that it was removed as being unnecessary.

2. Turbine and Compressors

The turbine and compressors are similar to those of the charge mode. As mentioned before, it is advisable to run a smaller turbine at night to avoid drops in efficiency.

The compressors should present a less severe materials problem than that of the charge mode since both of them compress a stream composed mostly of oxygen and because the outlet temperatures are lower.

3. Heat Exchangers

The heat exchangers for this mode (HE-2, HE-3, TRIM-3) are similar to those of the charge mode. The vaporizer (VAP-3), however, is the key to the entire process.

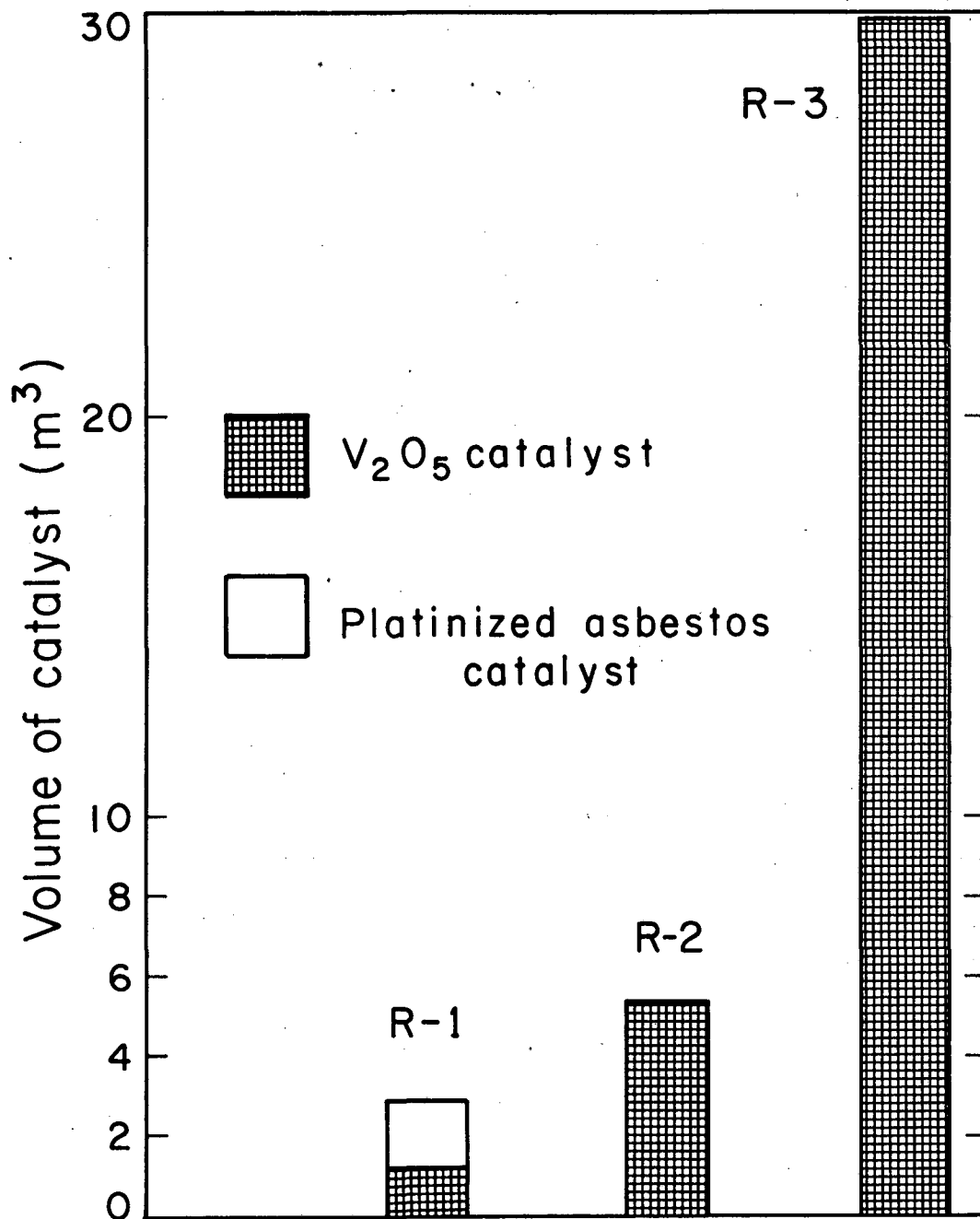


Fig. 4.3 Sizes of the Low Temperature Reactors

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It is necessary to ensure that there is sufficient heat in the stream leaving R-3 (30) to vaporize the SO_2 feed (20), as there is no heat available for this purpose from any other source. This sets a composition constraint on the SO_2 that is stored. There is thus a maximum in the fraction of SO_3 that can be allowed in the SO_2 used in the discharge process. This limit is set by the heat available from the process to vaporize the SO_2 - SO_3 . Its own latent heat cannot be recovered because SO_3 condenses in stream (32) at a temperature too low to provide the necessary heating.

The requirement of VAP-3 thus sets a constraint on the charge mode to ensure that the SO_2 stored is sufficiently enriched. This is accomplished by adjusting the exhaust pressure of the daytime turbine, thereby setting the fraction of SO_3 that has condensed at the outlet of TRIM-1. In the base case this results in a minimum turbine exhaust pressure of 2.5 bar. Greater pressures than this allow a more pure SO_2 product but result in less power produced by the turbine.

This same result would occur if the nighttime turbine exhaust pressure were raised. The stream would be hotter, leaving more heat available for vaporization. This was not found useful, however, as the generated power decreased rapidly while the change in the heat value of the outlet stream had little effect. The nighttime exhaust pressure was therefore set arbitrarily, and the daytime turbine-exhaust pressure was adjusted to meet VAP-3 requirements.

V. Storage Vessels

One problem associated with the storage of energy in this process is the large volumes required for the reaction products. An advantage of this process is that two of the reactants, SO_2 and SO_3 , can be stored as liquids and thus require less space than would equivalent quantities of gases.

The amount of liquid SO_3 that must be stored is 3.97×10^6 kg. At a density of 1760 kg/m^3 at 313 K this requires 2120 m^3 of storage volume. The SO_2 - SO_3 mixture stored is 3.43×10^6 kg. At a density of 1510 kg/m^3 at 313 K the volume required is 2140 m^3 .

It has been proposed that SO_2 and SO_3 could be stored in a series of mild steel pressure vessels.⁵ Since the need for storage for the two liquids varies during the cycle, the same vessels could be used to store the two liquids alternately. One tank could be filling with SO_2 as another was emptied of SO_3 , for example. This would greatly cut the number of vessels required, but would introduce the need for, and cost of, a complex piping arrangement. Since neither stream is very pure, there would be no disadvantage from the mutual contamination resulting from residual liquid in the tanks.

The containment of oxygen is more complex because it must be stored as a gas. The quantity to be stored each cycle is 0.54×10^6 kg for the base case. At a temperature of 313 K and pressure of 40 bar the corresponding volume is 9010 m^3 . In the present case the pressure in the vessel is 1.1 bar at the end of the cycle. This mass

of gas remaining in the vessel at the end of a cycle is about 1.1/40 or 2.8% of that above. This results in a total required storage volume of 9,260 m³.

Hill⁵ has suggested the use of cavern storage for storing such large quantities of gas. He proposed that a large excavated cavern could be dug, 300 m deep, so that the surrounding rock could support the pressure in the vessel. A mild steel lining would prevent leaks into the atmosphere or surrounding soil structure. Some provision would have to be made for collecting SO₂ condensate that would form as the gas cooled.

Cavern storage is economical only for large volumes; thus it is doubtful that it would be suitable for liquid SO₂ and SO₃. Separate vessels would have to be dug for each, and pumping costs would be large. These liquids need not be stored at high pressure, so the amount of steel required for pressure vessels is not excessive.

VI. Energy Accounting and Parameter Study

A. Energy Accounting

The efficiency of the overall process, defined as net electrical output, daytime and nighttime combined, divided by gross thermal input, was found to be 39.2% for the base case. The effect on the efficiency of changing some of the process parameters is shown in part B of this chapter. This high value was achieved by optimizing the heat exchange between the streams in the process.

The heat losses that do occur are caused by the low dew points of the streams entering the main trimmers, TRIM-1 (daytime) and TRIM-3 (nighttime). The substantial magnitude of these losses, along with the energy flows in the overall energy balance is given in Table 6.1. The heat of condensing the gases entering the trimmers which would be attractive for vaporizing the streams from storage is unavailable because of the low temperature at which it is released. The only way to usefully retrieve this heat would be to raise the turbine exhaust pressures. Unfortunately, this would also decrease the amount of power generated in the turbine.

Parasitic power drains were not included in the computer model of this process, but were calculated off-line and are also shown in Table 6.1. These power drains lower the efficiency shown in the parameter study from 39.6% to 39.2% for the base case. Pump requirements were calculated using standard equations using tube length and fluid velocity. Dry cooling energy drain was estimated to be 0.4% of the heat load of the trimmers.

Table 6.1 System Energy Accounting

I. Inputs (8 hours)	MW	MW-hr
Solar Receiver	230.0 (t)	<u>1840 (t)</u>
Total Inputs		<u>1840.0</u>
II. Outputs		
A. Daytime (8 hours)		
Generator	76.8 (e)	
Less		
Compressor	(24.5)	
Pumps	(0.7)	
Dry Cooling Tower	(0.3)	
TRIM-1	61.2 (t)	
TRIM-2	6.8	
Misc. (friction)		
Pump Cooling, etc.)	0.7	
Total Daytime Output	<u>120.0</u>	<u>960.0</u>
B. Nighttime (16 hours)		
Generator	21.6 (e)	
Less		
Compressors	(2.2)	
Pumps	(0.3)	
Dry Cooling	(0.1)	
TRIM-3	35.6 (t)	
Misc.	0.4	
Total Nighttime Output	<u>55.0</u>	<u>880.0</u>
Total Output		<u>1840.0</u>

The efficiencies of the turbines and compressors also play an important role in determining the overall process efficiency, as was shown in Chapter III. The effect here is on the power generated rather than on the amount of waste heat discarded. The inefficiencies of this equipment result in higher exhaust temperatures whose excess heat can be used elsewhere in the process.

B. Parameter Study

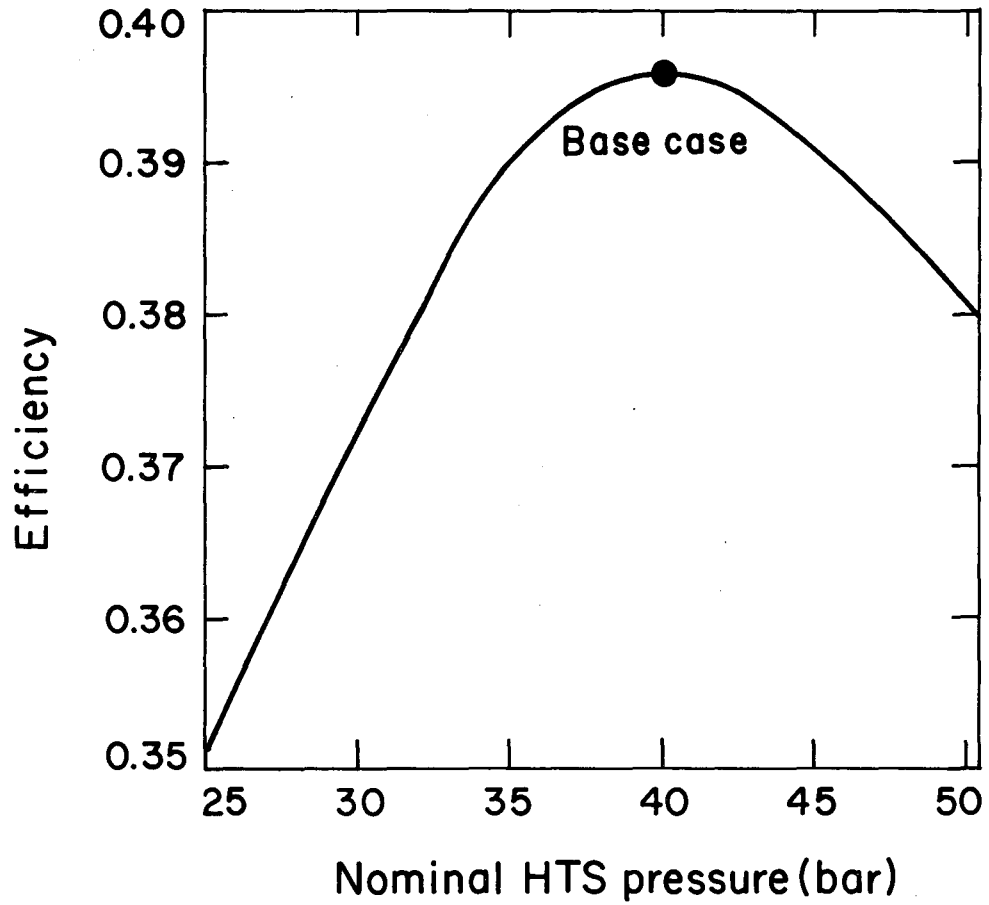
Some of the key parameters were varied in a computer study to determine the sensitivity of the efficiency of the process to changes in operating conditions. This also served to test the flexibility of the model. All the parameters other than the one being investigated in each case were at the base case conditions.

This study also helps pinpoint where further investigation would result in greater changes in efficiency and power cost. Costs are discussed qualitatively here, a more detailed treatment for the base case is made in Chapter VII.

1. System Pressure - Daytime

The effect of varying the daytime (HTS) system pressure on the overall efficiency is shown in Fig. 6.1. A range of pressures from 25 to 50 bar was investigated. The turbine exhaust pressure has been held constant at 2.5 bar because it is set by the composition constraints of the nighttime mode, which remain fairly constant.

The curve in Fig. 6.1 shows a maximum, which is a result of complex interactions within the system. At low pressures efficiency is low, since there is much less pressure drop across the turbine.



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Fig. 6.1 Effect of Daytime (HTS) Pressure on System Efficiency

Less daytime power is thus generated. In addition, at lower pressures the reaction equilibrium is improved so that a greater conversion is achieved. However, the greater conversion requires an increase in compressor power since more O_2 and SO_2 remain uncondensed in the stream leaving TRIM-1. Finally, the large flow of gas exiting the compressor (stream 12) contains more heat than can be used in the preheating the feed to the tower. This extra heat must therefore be discarded.

As the pressure is increased the efficiency also increases. More power is generated in the turbine. Conversion in the reactor decreases gradually, and the heat in stream (12) can be used more fully.

Finally, at about 40 bar, the efficiency reaches a maximum and starts to decrease. This is approximately where stream (12) is used only for preheating and can do no vaporizing. As the pressure is raised further, there is a greater pressure drop across the turbine. This still results in a greater work output per mole of gas flowing, but the number of moles of gas decreases because the fractional conversion of SO_3 to SO_2 and O_2 is reduced.

As the stream of recompressed gas (12) continues to decrease in size, its enthalpy becomes insufficient to heat the tower feed (4) to its bubble point. This heat must then be supplied by the turbine exhaust stream (7), which in turn leaves less available for vaporization and superheating. The temperature of stream (4) thus decreases.

As the temperature of the gas entering the solar receiver (4) falls, a larger fraction of the thermal insolation must go to make up for the lost superheating. This duty is limited, however, by the constraint that HE-1 and the reactor can absorb only a total of 230 MW_t . As a result, the flow of gas through the system must decrease. This results in less daytime power being generated.

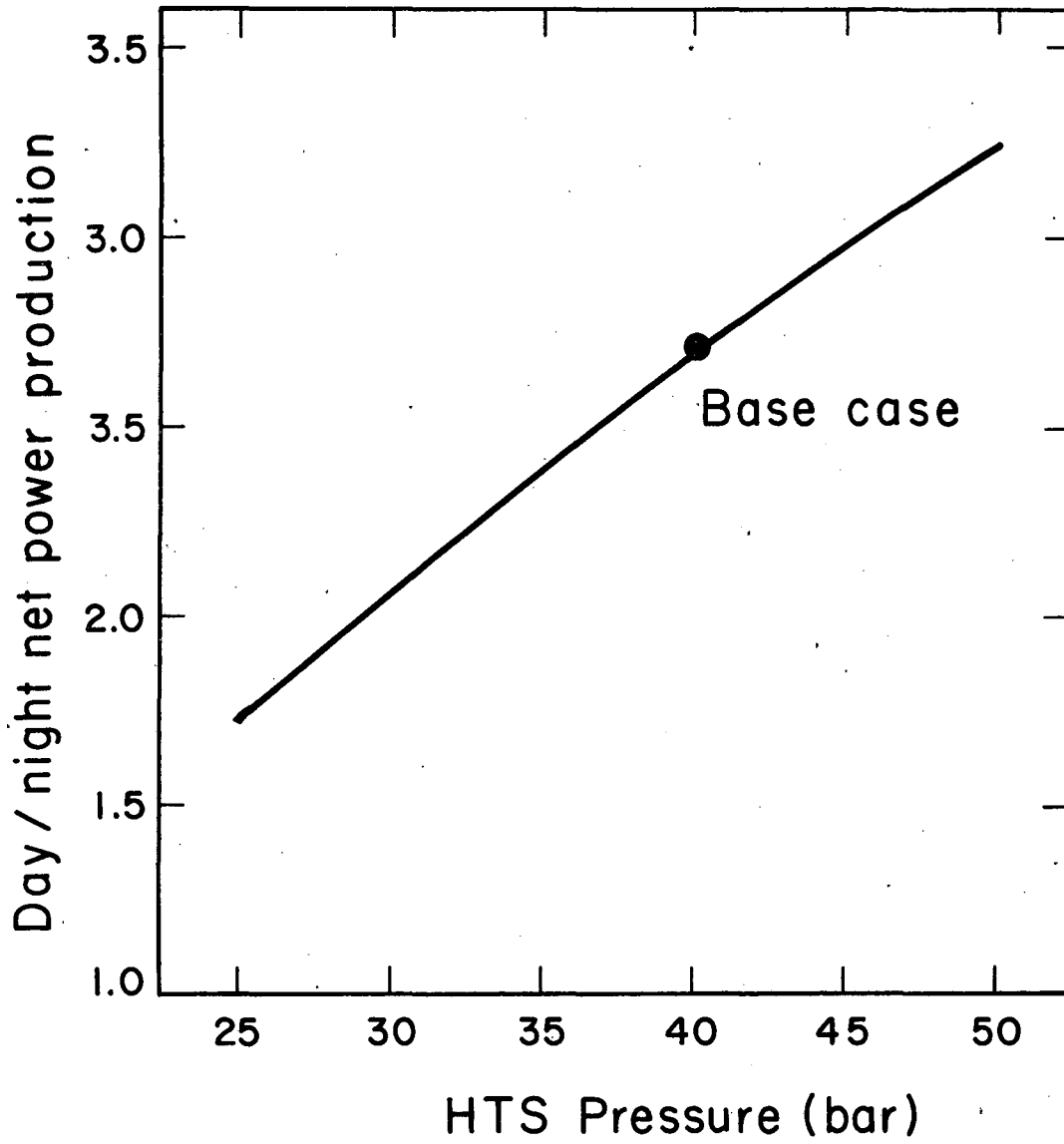
Some considerations other than efficiency affect the pressure chosen. One is materials limitations. As the pressure is increased it becomes more difficult for the tubing to contain the stream; thicknesses increase and lifetime probably decreases.

Another consideration is the ratio of daytime to nighttime power production, shown in Fig. 6.2. This ratio is fairly sensitive to pressure of the HTS because not only does a lower pressure result in more reaction and thus more nighttime power production, it also causes more compressor drainage of daytime power. These two factors combine to lower the daytime power production and raise that for the night as pressure increases.

2. System Pressure - Nighttime

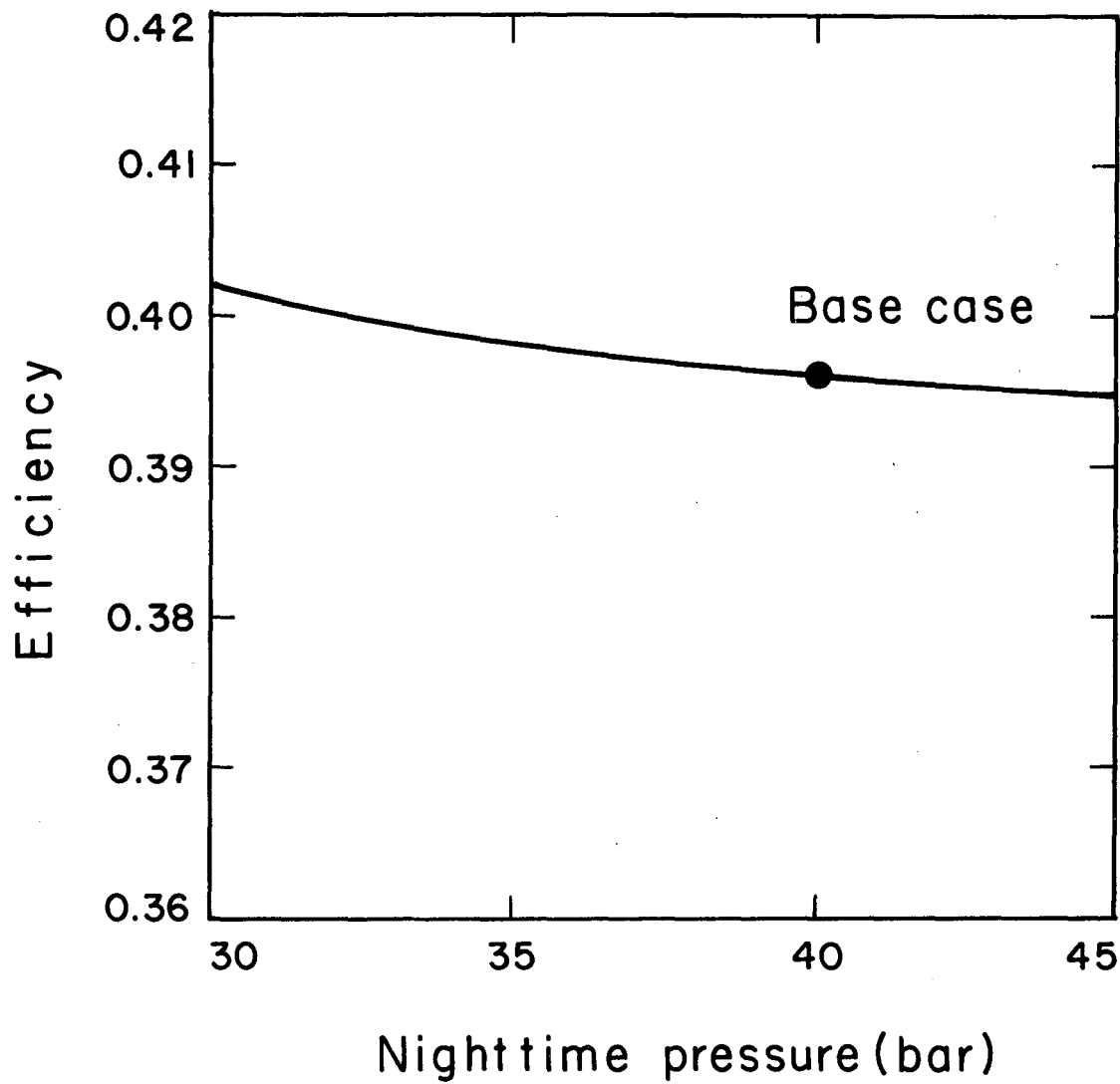
The effect on overall efficiency of varying the nighttime, or LTS, system pressure is shown in Fig. 6.3. A pressure range of 30 to 45 bar was investigated.

The system efficiency clearly increases with decreasing nighttime pressure. This actually results primarily from the effect on the daytime operation, since the nighttime operating conditions do not change much in this pressure range. Reducing the LTS pressure,



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Fig. 6.2 Effect of Daytime Pressure on Day/Night Power Ratio



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Fig. 6.3 Effect of Nighttime (LTS) Pressure on System Efficiency

however, does substantially affect the amount of daytime compressor work required, since the oxygen is stored at the LTS pressure. As the pressure decreases, less of the daytime turbine power need be drained by the compressor.

The choice of an optimal nighttime pressure is not immediately obvious, as process efficiency must be balanced with storage costs. As the pressure decreases, the volume of oxygen storage required correspondingly increases. No savings in materials results, since the carbon steel lining in the O_2 cavern is only used to prevent leaks. An analysis of total costs must be made to determine the optimum.

Other considerations for choosing a nighttime pressure are similar to those of the daytime. Materials requirements will again be a concern. As the nighttime turbine will also be in use during the day, these operating conditions must be chosen such that they are compatible for the turbines. The ratio of day/night power production can also be set by the nighttime pressure. This again is a result of the drain of power by the daytime compressor.

An alternative scheme could be to compress the gas to a higher pressure during the day, perhaps 50 bar. This would reduce storage costs. The volume of gas would decrease at higher pressure, and more SO_2 would condense. It is preferable to store the SO_2 as a liquid rather than as a gas, although the amount (about 9% of the gas) is not great. A turbine could generate electricity during the night from the stored oxygen as it was expanded to the pressure chosen for the nighttime cycle.

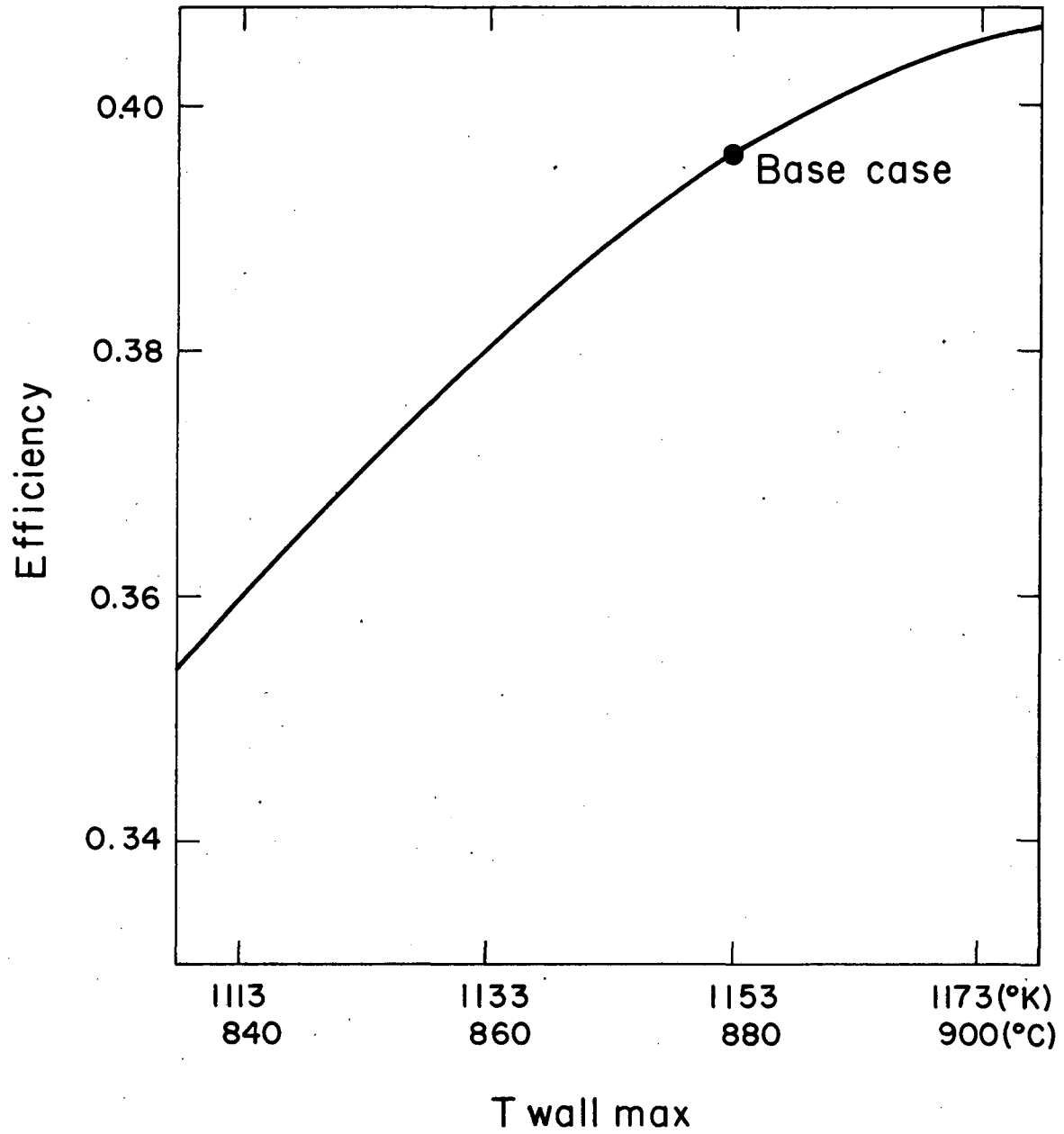
3. Maximum Tube Wall Temperature

The effect on efficiency of varying the maximum wall temperature of the tubes in the receiver is shown in Fig. 6.4. A temperature range of 1113-1193 K (840-900°C) was investigated. This is not a fully adjustable parameter as materials place an upper limit on this temperature.

The primary effect of varying this temperature is on the equilibrium conversion in the receiver-reactor. As the temperature is increased, the conversion of the SO_3 in the stream flowing through the reactor is increased, so that more reaction product is stored. Night-time power production thus increases. The larger size of stream (12) results in a greater compressor drain of the daytime power, but all of this heat can be used for heating the tower feed.

Another effect of raising the allowable temperature is on the power production in the daytime turbine. The higher temperature of stream (6) and the increased number of moles of gas in it allows greater electricity production from the turbine. The overall efficiency thus increases.

The sharp decrease in efficiency as the tube wall temperature is lowered indicates the usefulness of achieving the highest temperatures possible. An optimization should be done to correlate the economics of increased efficiency with the cost of more frequent replacement of reactor and turbine components.



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Fig. 6.4 Effect of Receiver Tube Tube Temperature on System Efficiency

4. Minimum System Temperature

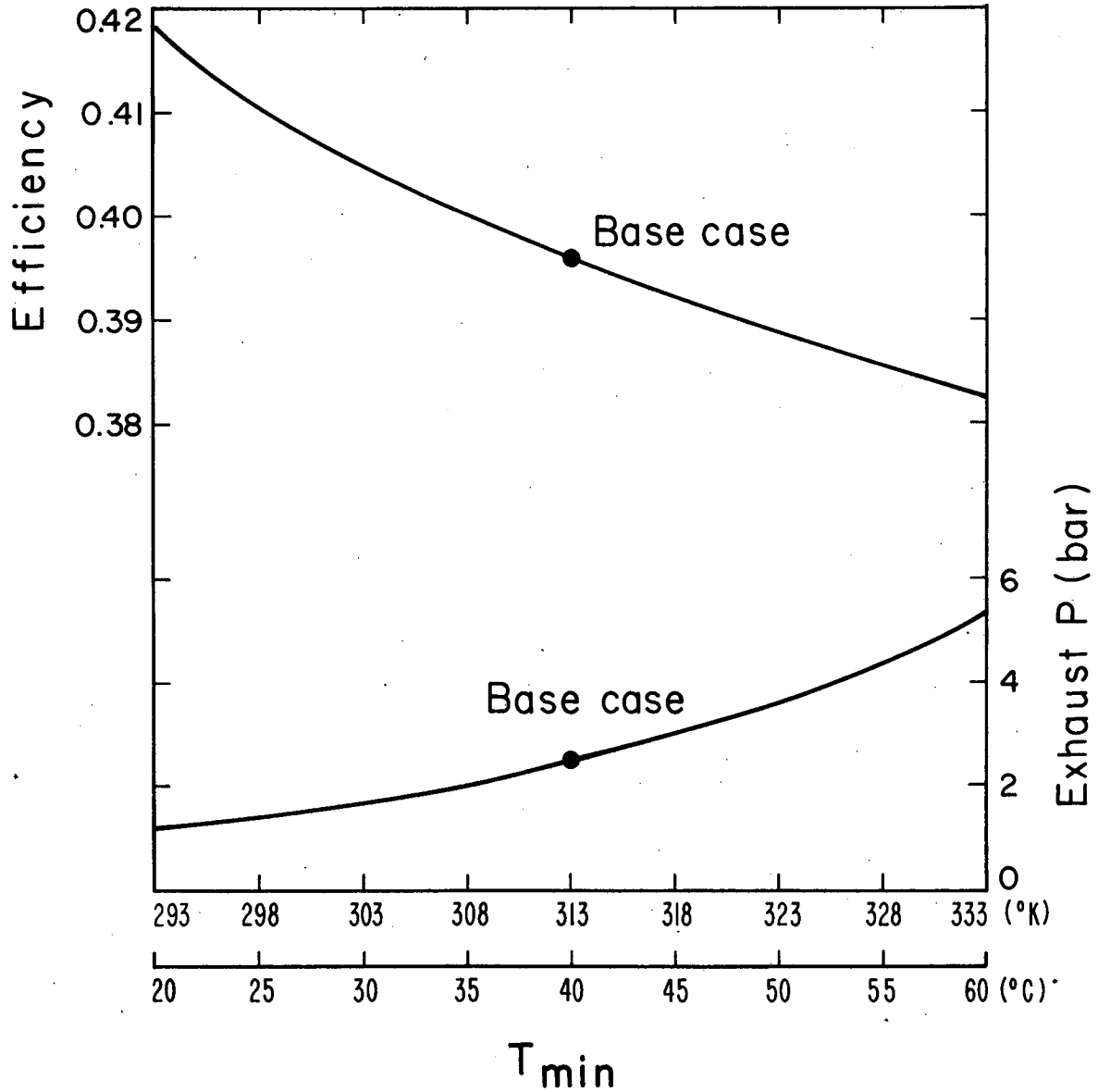
The effect of changes in the minimum temperature achievable in this system is shown in Fig. 6.5. A range of 293-333 K (20-60°C) was investigated. For design purposes the ambient temperature was taken to be 10°C lower.

This minimum system temperature is of course not freely adjustable but is determined by the weather. The temperature range chosen corresponds to that expected for a desert environment. In these calculations a constant temperature for the day and night was used. In reality, the temperature would be a function of both time of day and season.

As with most thermodynamic cycles the efficiency was found to increase as the minimum temperature decreased. The major reason for this is the decreasing daytime turbine exhaust pressure, also shown in Figure 6.5.

As explained in Chapter III, this exhaust pressure is determined by the SO_2 - SO_3 vaporizer requirements in the nighttime process. This in turn is set by the SO_2 content of the stream stored (17). As the temperature of the stream leaving TRIM-1 decreases, its pressure may be lowered while maintaining the same amount of condensation and recycle. The result is a greater turbine output since the pressure drop across it increases.

Lowering the minimum temperature also serves to recover more of the heat of condensation of the exhaust streams. Some of the SO_3 in



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Fig. 6.5 Effect of Minimum System Temperature on System Efficiency and Turbine Exhaust Pressure

the exhaust stream condenses while heating the feed streams to a temperature within 10°C of it. This occurs in both the daytime and nighttime modes.

A related benefit of reducing the minimum temperature is that more SO_2 condenses out of the O_2 stream at lower temperature. During the day this allows storage of more SO_2 as a liquid rather than as a gas. During the nighttime this reduces the size of the O_2 stream that must be recompressed and recycled.

VII. Cost Analysis

A. System Costs

The costs for installed equipment and operation for the base case conditions were estimated for purposes of comparison. These costs include process piping, electrical connections, control systems, engineering, etc. They do not include plant auxiliaries such as land, roads, and fences. Cost indices published in Chemical Engineering were used to adjust all costs to June, 1979.

Some costs for fabricated equipment were based on the weight of the metal used. The price taken for fabricated pressure vessels was \$3.50/kg for carbon steel⁶ and 4.25 times this for 316 stainless steel (7), or \$14.80/kg. Installation costs were taken to be 140% of fabricated costs.⁸ In-place equipment costs thus are 2.4 times the fabricated cost for carbon steel equipment.

1. Tower, Receiver, and Mirror Field

The cost of these items is the most uncertain of any component in the design, as nothing similar has ever been built. This cost is also a substantial fraction of the total cost of the process. The uncertainty in cost becomes less important, however, when comparing this process with other systems of solar power generation and storage. Presumably these other systems will use a similar tower and mirror field. This allows a comparison before the costs of these items have been more accurately determined.

Boeing² has estimated the costs of a tower, mirror field, and receiver absorbing 230 MW_t to be \$40.5 million in mid-1976.

Adjusting to mid-1979 the cost is:

$$\$40.5 \times \frac{(236)}{(192)} = \$49.8 \text{ million}$$

This figure is based on a mirror cost of $\$65/\text{m}^2$. This is an estimate for mass-produced heliostats and is not presently obtainable. The cost with present technology would be higher.

The receiver in this process is modified in that Fe_2O_3 catalyst is coated on the inside of the reactor tubes. While difficult to estimate, the catalyst and labor costs are expected to be minor in comparison to the other costs for the receiver and heliostats.

2. Turbines and Electric Plant

Boeing² has estimated the cost for a gas turbine process using the Brayton cycle to be $\$119/\text{kW}_e$ of net power in mid-1976. This cost, however, includes the cost and power drain of the compressor in their cycle. By allowing for the cost and power requirement for the compressor we estimate a turbine cost of roughly $\$41/\text{kW}_e$ for a 100 MW_e gas turbine. Adjusting to mid-1979 the cost is $\$50/\text{kW}_e$.

For the present process two turbines, one of 60 MW_e and one of 20 MW_e capacity, are proposed. In scaling the costs down from a 100 MW_e turbine, cost was assumed to be proportional to the 0.6 power of the capacity. This resulted in a total turbine cost of $\$6.7$ million. Better estimates should be made in the future as this is a large fraction of the total cost of the power plant.

Boeing used a cost of $\$20/\text{kW}_e$ of net generated electricity for the generators and electric plant. In mid 1979 this would be approximately $\$24/\text{kW}_e$. Since the net power generation during the day is 53.2 MW_e , this results in an electric plant cost of $\$1.2$ million.

3. Compressors

The costing of compressors is a standard calculation and is based on the gas flow rate and number of stages required. Costs were taken from Peters and Timmerhaus⁸ and adjusted to mid-1979. The daytime compressor (C), with a load of 24.5 MW_e, has an installed cost of \$850,000. The nighttime O₂ recycle compressor (C-2) with a load of 1.6 MW_e, costs \$170,000. The compressor for pumping O₂ from storage has a load that increases with time as the chamber is emptied. For this reason, two compressors are used, each with a maximum load of 0.6 MW_e and costing \$93,000. The total cost for compressors is thus \$1,210,000.

4. Heat Exchangers

Calculations for estimating heat-exchangers sizes were made for each exchanger required, using heat-transfer coefficients from standard correlations. Costs were estimated according to Popper⁹ and include installation, materials, and pressure factors. Air cooled trimmer costs were taken from Perry.¹⁰ Stainless steel was used for all heat exchangers, and a material factor of 4.5 over carbon steel was taken. An installation factor of 1.3 was used.

The sizes and costs of all exchangers including piping, electrical connections, and control systems is shown in Table 7.1. More detailed information about the sizing procedure used is given by Hill.⁵

A possible modification to reduce costs is to use the same heat exchangers for both day and night. At a cost of more complex piping

Table 7.1 Heat Exchanger Sizes and Costs

Heat Exchanger	Type of Heat Transfer	Heat Duty (MW)	Area (m ²)	Installed Cost (\$1,000)
Daytime				
COND-A	cond. gas-liq.	65.2	2,810	1,980
COND-B	gas-liq.	23.1	2,350	1,640
VAP-1	gas-vap. liq.	1.4	12	18
VAP-2	gas-vap. liq.	87.7	650	500
TRIM-1	cond. gas-air	61.2	3,430	930
TRIM-2	cond. gas-air	6.8	300	107
Nighttime				
HE-2	gas-gas	4.0	27	35
HE-3	gas-gas	11.3	708	123
VAP-3	gas-vap. liq.	33.1	470	400
TRIM-3	cond. gas-air	35.6	1,500	<u>414</u>
Total Installed Cost				\$6,150,000

June 1979

this can eliminate the need for any different exchangers for the nighttime (LTS) process. The effect of this modification on the cost of power, however, is small.

5. Storage Vessels

The volumes required and means of storage of SO_2/SO_3 and oxygen are discussed in Chapter V. Liquid SO_2 and SO_3 are stored jointly in a number of spherical carbon steel tanks. The thickness of each tanks is determined by the diameter and the pressure differential (7 atmospheres) across the walls.

The total steel required for 35 vessels 5.3 m in diameter and 1.35 cm thick is 171,400 kg. This results in a fabricated cost of \$620,000 and an installed cost of \$1.48 million. The total volume of these vessels is 2730 m^3 , which represents an SO_3 capacity of 5×10^6 kg.

During an emergency it may be necessary to store hot $\text{SO}_2\text{-SO}_3$ streams to drain the system. Several of the tanks should be constructed of stainless steel to allow for this possibility. This would have a small effect on the total storage costs.

The costing of an oxygen storage vessel is more difficult as cavern costs vary widely with the size and depth required. Cost estimates run from $\$6.5/\text{m}^3$ to $\$390/\text{m}^3$.¹¹ The former cost is for large shallow caverns, the latter for small, deep ones. This results in a range of costs from \$0.06 to \$3.61 million for a volume of $9,260 \text{ m}^3$. The cavern in this process is at neither extreme, so a cost of $\$220/\text{m}^3$ is used in these calculations. This results in a cavern cost of \$2.0 million. Further work by industry with the excavation of caverns for fluid storage should result in better estimates.

6. Nighttime Reactors and Catalyst

The low-temperature reactors consist of three beds with vanadium pentoxide catalyst and one with platinized asbestos. The scheme proposed is to have the three reactors in three shells. The first shell contains R-1, a V_2O_5 and platinum bed in series. The total volume of the catalyst is 2.9 m^3 . The shell volume is taken to be slightly larger (3.2 m^3) to allow for gas distribution. The gas pressure drop in this reactor and in each of the others in this system is 0.2 bar. The shell thickness is 5.5 cm for operation at 40 bar, resulting in a mass of steel of 4500 kg.

The second shell contains R-2, which has 5.4 m^3 of catalyst (V_2O_5). This is a radial flow reactor to keep pressure drops low while allowing reasonable reactor dimensions. The total volume of this shell is 7.1 m^3 . The shell thickness of 0.8 cm for operation at 2 bar results in a steel mass of 1230 kg, including center support.

The third shell contains the largest reactor, R-3. This has a catalyst volume of 30.0 m^3 and also has radial flow. The total shell volume is 36.5 m^3 . The shell thickness is 0.8 cm and the mass of steel is 3280 kg.

The total steel required for the three reactor shells is 9020 kg. This results in a fabricated cost of \$134,000 and an installed cost of \$320,000.

Vanadium pentoxide costs depend on the source, quantity, and support used. The total mass of supported V_2O_5 used in the reactors is 29,100 kg. Cost data from vendors indicate that the purchased cost of this much catalyst would be \$71,800.

Platinum catalyst costs were more difficult to ascertain than those for vanadium pentoxide. Fortunately, the amount required is small. The cost of the catalyst was taken to be the value of the platinum metal plus 10% for processing.

The platinized asbestos catalyst, containing 7% platinum by weight, contains 3.39 kg (108.8 troy oz.) of platinum. At the current market price of \$350 per troy ounce, plus 10%, the cost of the catalyst is \$42,000.

A credit may be taken for platinum recovery from the spent catalyst. Approximately 90% of the metal is recovered. The value of this credit is \$34,000, leaving a net catalyst cost of \$8,000.

7. Reactants

The most logical way to ship the reactants to the project site is as liquid SO_3 . This eliminates the need to transport large quantities of oxygen if SO_2 were shipped. A large amount of SO_3 is needed, approximately nine 35,000-gallon tank cars must be provided for the base case daily cycle.

According to Boeing,² liquid SO_3 costs about 92% as much as SO_2 per ton. Although not as common as SO_2 in chemical trade, SO_3 should be readily available from any manufacturer of oleum, which is a solution of SO_3 in H_2SO_4 . Should this process be implemented in large scale, a grass-roots sulfur oxidation plant could be set up for producing SO_3 .

According to the Chemical Marketing Reporter for June 1979, the average cost for SO_2 when purchased by the tank is \$158 per ton. Adjusting for SO_3 costs, a total reactant cost for 4.0×10^6 kg of SO_3 would be \$640,000.

8. Dry Cooling Tower

The design of the dry cooling tower and system is beyond the scope of this project. A rough estimate of the cost of this tower for a "Heller" type system was taken from Rossie and Cecil.¹² The updated costs are \$33,100 per MW_t of heat load. The load consists of the heat rejected in the trimmers. During the day this load is 68 MW_t , and in the night 35.6 MW_t . The tower cost is thus set by the daytime load and is \$2.25 million.

A summary of major equipment costs is shown in Table 7.2. It is clear that the tower, receiver, and heliostats are the major costs of this process. Turbines and heat exchangers were found to make up a large portion of the remainder. These are thus the first components that should be subject to further study and cost estimation.

B. Cost of Power

The cost of the electricity produced by this process (cents per kW-hr) was estimated from the capital cost by using a capitalization rate and a stream factor. The capitalization rate chosen for equipment not in direct contact with the $\text{SO}_x\text{-O}_2$ streams was 18% per year. This applies to the tower and heliostat field and the dry cooling tower. This is three percentage points higher than that used

Table 7.2 Summary of Equipment Costs

Total Plant Costs (\$1,000)	
Tower, Receiver, Heliostats	\$49,800
Turbines and Elec. Plant	7,900
Compressors	1,210
Cooling Tower	2,250
Heat Exchangers	6,150
Low Temperature Reactors and Catalysts	400
Reactants	640
Storage Vessels	
SO ₂ - SO ₃	1,480
O ₂	<u>1,970</u>
Total Plant Cost	\$71.7 Million

by Skinrood.¹³ The higher figure was taken to allow for the increased maintenance for the receiver tubes, which is expected because of their contact with the hot, corrosive gases.

For highly corrosive conditions Peters and Timmerhaus (8) suggest an even higher capitalization rate. They estimate an increase of about 10 points to account for more frequent maintenance and replacement. A rate of 25% of the installed equipment cost per year is therefore used for the equipment exposed to corrosive gases.

Using a stream factor of 0.7 (256 days/year) the cost of power at the base case conditions is:

$$\begin{aligned} \text{Cost} &= \frac{(49.8 + 2.2) (0.18) + (19.7) (0.25)}{256(8(53.2-0.7-0.3) + 16(19.4-0.3-0.1))} \\ &= \$7.73 \times 10^{-5} / \text{W-hr} \\ &= 7.73 \text{¢} / \text{kW-hr} \end{aligned}$$

Figure 7.1 shows the effect of different stream factors on the cost of power. Fig. 7.2 shows the effect of different periods of insolation, ranging from 6 to 14 hours per day, on the cost of power. Only minor changes in storage costs result from this variation. Both of these parameters are set by the weather conditions.

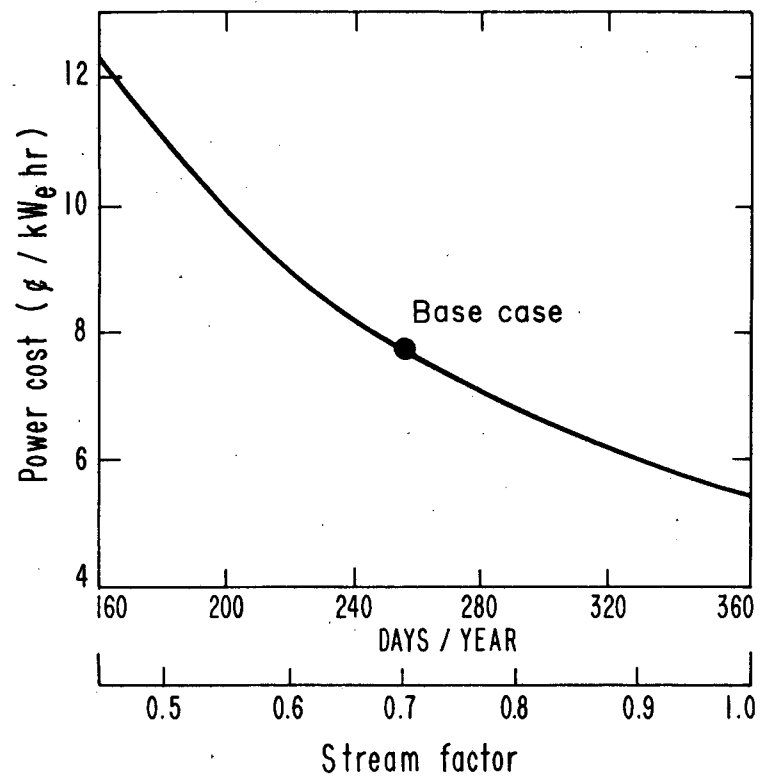
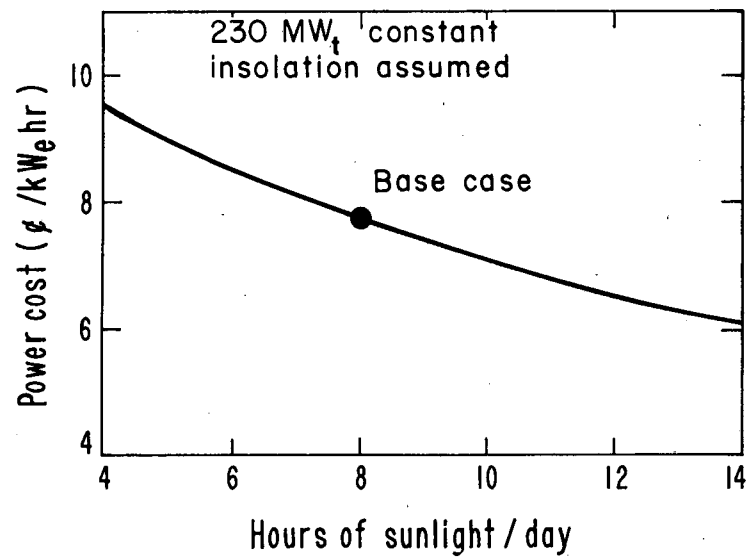


Fig. 7.1 Power Cost vs. Stream Factor



XBL 797-2225

Fig. 7.2 Power Cost vs. Hours of Sunlight per Day

VII. Comparison with Alternative Energy Storage Processes

To provide some perspective, this process is compared with alternative energy storage schemes that have been proposed for solar power plants. The bulk of this comparison is made with an alternative sulfur oxide process as reported by Dayan et al.³ A short description of their process appears in Chapter I.

Dayan's process involved a sulfur oxide storage system integrated with a solar steam plant. During the day, water was vaporized in tubes contained in part of the receiver. This served as the steam boiler for daytime power production. The remainder of the receiver contained tubes through which SO_3 flowed and reacted. The SO_2 and O_2 produced were cooled, separated from SO_3 and sent to storage.

During the night the heat liberated by the reacting SO_2 and O_2 was used to vaporize water in a conventional steam cycle. The train of reactors and heat exchangers was similar to the gas turbine process. The resulting SO_3 was cooled and sent to storage.

The installed equipment costs for the two processes are shown in Table 8.1. Dayan's figures have been adjusted to June 1979. The two sets of figures can be readily compared since the same methods and sources were used to estimate costs in each case. Similar base case conditions were used, with nearly identical tower-receivers.

The total costs for the two processes are clearly very similar. The distribution of the costs of the components is quite different, however. The steam turbine is much cheaper, primarily because electrical output is much lower. The steam turbine produces 31 MW_e

Table 8.1. Plant Costs of Gas Turbine and Steam Turbine Processes

	Plant Cost*	
	Steam Turbine	Gas Turbine
Tower, Receiver, Heliostats	\$49.8x10 ⁶	\$49.8x10 ⁶
Turbines and Generating Plant	4.3	7.9
Compressors	-	1.2
Cooling Tower	2.9	2.2
Heat Exchangers	10.3	6.1
Distillation Column	0.7	-
Low Temperature Reactors and Catalysts	0.9	0.4
Reactants	0.4	0.6
Storage Vessels		
SO ₂ - SO ₃	1.0	1.5
O ₂	<u>3.3</u>	<u>2.0</u>
	73.6x10 ⁶	\$71.1x10 ⁶

*All costs are June, 1979 dollars.

during the day, while the gas turbine generates approximately 78 MW_e. No compressors are required for the steam turbine, but no distillation column is used for the gas-turbine process. Heat exchangers costs are much lower in the gas turbine plant, since less heat-exchange area is required.

Other differences between the steam and gas-turbine plants are relatively minor. The steam plant requires a larger dry cooling tower due to its greater waste heat disposal. This is a result of its lower efficiency, which is discussed below. The reactors in the steam plant are more costly because they operate at 11 bar, necessitating a metal thickness greater than that of the 2-bar reactors used in the gas-turbine process. Reactants (SO₃) and liquid storage costs are higher for the gas-turbine plant because the streams are less pure. This is a result of omitting the distillation column used in the steam process. Less of the O₂-SO₂ mixture is stored, and this is reflected in a lower O₂ storage cost.

The cost of power, as shown in Table 8.2, shows the real difference in the economics of the two processes. Electricity costs about 34% less with the gas-turbine process. Since the equipment costs are similar, this is a direct result of the different efficiencies of the two processes. Some of the key energy accounting figures are also shown in Table 8.2. Both processes absorb 230 MW_t during an 8-hour day and discharge power from storage for a 16-hour night. Cost figures were based on identical capitalization rates and stream factors.

Table 8.2 Energy Accounting and Power Costs for the Steam Turbine and Gas Turbine Processes.

	Steam Turbine	Gas-Turbine
Energy Absorbed (MW_t -hr 1 Day)	1840	1840
Energy Released		
Daytime Net Electrical Output (MW_e -hr/Day)	255	418
Steam Cycle Condenser (MW_t /Day)	263	—
Process Waste Heat (MW_t -hr/Day)	513	545
Nighttime		
Net Electrical Output (MW_e -hr/Day)	250	304
Steam Cycle Condenser (MW_t -hr/Day)	459	—
Off-line Turbine Bleed (MW_t -hr/Day)	34	—
Process Waste Heat (MW_t -hr/Day)	66	570
Total Energy Released (MW -hr/Day)	1840	1840
Overall Efficiency (%)	27	39
Cost of Power ($\text{¢}/kW_e$ -hr)	11.2	7.7

The steam-cycle power plant and storage process have a low efficiency for several reasons.

1. The steam-cycle efficiency is limited to about 40% of the heat it absorbs. Vast amounts of heat must be discarded in the condenser of this cycle. This figure is much lower during the day because a large amount of low pressure steam must be channelled to the storage process. This correspondingly increases the process waste heat.

2. The steam turbine must be kept hot and turning during the night to allow rapid start-up at sunrise. A bleed stream of steam must thus be effectively wasted to allow this. Although the amount of heat is relatively small, it is of high quality and could be converted directly into electricity. This bleed is not required in the gas turbine process.

3. The steam process has in addition unusable heat of condensation of SO_2 and SO_3 . Trimmers discard this heat much the same way as they do in the gas-turbine cycle. The trimmer loads are much less in the steam process because the cycle is isobaric, allowing more recovery of the heat of condensation.

Other factors should be taken into account when choosing between the two processes. Even though the use of SO_2 - SO_3 as the power fluid in the gas-turbine process increases the efficiency, it can lead to more severe corrosion and fatigue problems. These problems would appear in the turbines and compressors, the only components where the two processes are significantly different.

Although both processes are subject to uncertainties in their operation, design, and costs, the gas-turbine process appears to be by far the superior of the two. It would seem therefore that further work should be initiated on the gas-turbine process prior to any further study of the steam-cycle storage process. Further discussion of the uncertainties is given in Chapter IX.

Another process for the storage of solar energy is currently being investigated in our laboratory by Baldwin.¹⁴ His is a sensible-heat process using a checkerwork of magnesia bricks in cast iron vessels. The vessels are in series with the boiler of a steam-cycle power plant. A gas such as helium or nitrogen is used to transport heat from the central receiver. Using a similar tower, mirror field, and receiver Baldwin has calculated a power cost of 8.7 ¢/kW-hr. Capitalization rates and stream factors similar to those of this study were used to obtain this figure. This power cost is too close to that of the gas-turbine process to choose between them at this time on the basis of economics. Baldwin does not have the uncertainty of corrosion as in the gas-turbine process, but thermal losses restrict the use of sensible-heat storage for periods much longer than 24 hours.

IX. Conclusions and Recommendations

The economics of electricity production using the gas-turbine process described in this report appears to be very attractive, although the accuracy of this estimation is highly uncertain. The estimated power cost of $7.7\text{¢}/\text{kW}_e\text{ hr}$ is high compared to current fossil-fuel-fired power sources, but only by a factor of about 2. In view of the rapid escalation of fossil fuel costs, this discrepancy is low enough to warrant further investigation. Furthermore, the continuing problems of environmental safety associated with the use of fossil and nuclear fuels may make this alternative means of energy production and storage become increasingly attractive.

Since the primary cost of solar energy from a "power tower" operation lies in the cost of the mirror field, a method of producing electricity from this solar energy can only be economically attractive if its efficiency is high. The novel hybrid of the Brayton and Rankine cycles described in this report has the potential for high efficiency because it utilizes the thermodynamic potential of the high temperatures that obtain in the process. The primary uncertainty in the economics estimates presented here arises from the corrosiveness of the system at the temperatures required. A developmental program will be needed to determine whether economically as well as technically feasible solutions exist for the materials problems that will be faced.

A. Verification of Assumptions

The novelty of this design has made a large number of assumptions regarding physical properties necessary. Experimental verification or more sophisticated modeling should be performed on the following.

1. Tower, mirror field, and receiver costs and construction are very unfamiliar and need to be investigated further. Solar systems using these components, however, may be compared in the interim by using similar estimates of costs. The practicality of coating Fe_2O_3 on the receiver tubes must be determined, as well as the costs of the catalyst and its installation.

2. Problems of materials compatibility have been mentioned, and they require experimental testing. The performance of the turbine exposed to corrosive gases should be determined, including the effects on the bearings, lubrication, and seals. The adherence of protective oxides and sulfides to the metal must be determined under conditions of thermal cycling.

3. Heat and mass-transfer correlations used to model the receiver-reactor and to size heat exchangers can have an accuracy of only +50%. This will necessitate experimental investigation of these models.

4. The process is very sensitive to the efficiency of the turbines, as shown in Chapter III. A more accurate estimate of this efficiency must be made, as power costs are sensitive to it.

5. Cavern storage of oxygen should be investigated more thoroughly, as only a rough estimate of cost was used. Further, there are technical problems of flow of oxygen at high flow rates.

6. This process uses heat exchangers that are huge by most standards. The physical design and cost estimates need to be more accurately determined.

7. Capital cost calculations were simplified by the omission of plant auxiliaries and by using set installation factors for all equipment. A detailed estimate would allow greater confidence in these figures.

B. Sensitivity Analysis

The parameter study (Chapter VI) provided some insight as to the most desirable operating conditions. It was not, however, a true optimization, as only one parameter at a time was varied. The novelty of this combined Brayton-Rankine cycle has given it unusual responses to parameter variations, and a more sophisticated modeling may yield a cycle with better performance than the current base case.

1. The process efficiency has strong dependence of the daytime pressure. Our model indicates that the pressure chosen should be in the range of 38-42 bar.

2. The nighttime pressure has a weak effect on efficiency and is not particularly important. The cost of power should be minimized by balancing the economics of changing this efficiency with the effect on the cost of storage and heat exchangers.

3. The study of how efficiency varies with the maximum temperature achievable in the reactor walls ($T_{\text{wall max}}$) shows the importance of reaching the highest temperatures possible in the reactor. This requires a more involved cost analysis to account for the more frequent replacement of these tubes at higher temperatures.

4. The process efficiency has a strong dependence on the ambient temperature because of its influence on the process discharge temperature. Since the 40°C discharge temperature of the base case is a conservative estimate, the process will probably run at an efficiency higher than 39% most of the time. This would allow removal of some of the heliostats from the matrix for maintenance. Alternatively, more SO₂ and O₂ could be stored during the daylight hours. This is a fortunate result, as the winter days have fewer hours of sunlight.

This process is strongly dependent on the ambient and operating conditions, and will require complex control as these change during the day or year. An analysis of how this control should be designed and implemented is a subject worthy of further study.

C. Modes of Operation

This process has been designed and the costs ascertained for the simplest of scenarios; constant insolation for a set period of time and constant discharge for the remainder of the day. This was necessary to test the economics under favorable conditions prior to any further investigation. Some other possibilities are:

1. It may be desirable to run the discharge mode at variable rates, to allow for higher mid-evening power requirements, for example. This would require large nighttime equipment: reactors, heat exchangers, etc. The added flexibility of the process would probably be worth the increase in capital cost that would result.

2. One advantage of this storage process over others is the possibility of running the charge and discharge modes simultaneously. This would be useful at about 6:00 P.M., for example, when the sun is perhaps not supplying adequate power. The cost is the loss of the possibility of using some heat exchangers for both modes, as discussed in Chapter VII. The gain is that no additional equipment need be used if the charge mode can lend some of its excess turbine capacity to the discharge mode. This is another advantage to having a number of small turbines.

3. Depending on cost and locational restrictions, additional storage capacity could be constructed for longer term storage. SO_2 and O_2 could be stored during weekends, a period where demand is lower, to be used gradually through the week.

The high cost of storage would seem to rule out long-term seasonal storage, such as from summer to winter. A quantitative analysis of seasonal storage has not been made in this study, but likely ranges of storage times should be investigated.

D. Conclusion

Although fraught with assumptions and estimations, this study shows that the gas-turbine process appears to have attractive economics at this stage of its development. Further work on some of the problems and uncertainties mentioned herein is a worthwhile next step.

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Appendix A. Turbine and Compressor Computational Technique

1. Turbines

The program first calculates the adiabatic reversible change in enthalpy of the stream through the turbine, using the pressure drop previously set. This is represented by the isentropic path from point 1 to point 2 in Fig. A.1. This path is calculated by determining T_2 from the pressure ratio and the heat capacity of the stream. The equation used is

$$\frac{T_2}{T_1} = \frac{P_2}{P_1}^{\frac{\gamma-1}{\gamma}}$$

where $\gamma = C_p/C_v$. H_2 is found by routine ENTR2, knowing the temperature and composition.

To allow for turbine irreversibility, an efficiency of 90% was assumed in the base case. This results in a real endpoint of 2', where $H_1 - H_{2'}$ is equal to 90% of $H_1 - H_2$. This expansion path is shown by the dashed line 1-2'. The turbine electrical output is this ΔH times the flowrate through it. The program calculates the enthalpy of the exiting stream, $H_{2'}$, by subtracting this ΔH from H_1 . It then calculates the temperature corresponding to that enthalpy by calling routine FINDT.

2. Compressors

For the compressors the reverse procedure is essentially used. This procedure is illustrated in Fig. A.2. The program calculates the isentropic adiabatic compression of the stream from point 1 to 2. To

Fig. A.1 P-H Diagram for Expansion (Turbine)

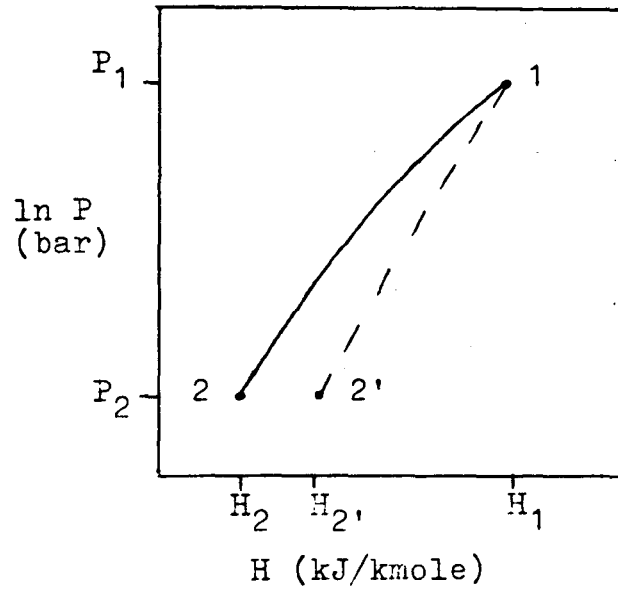
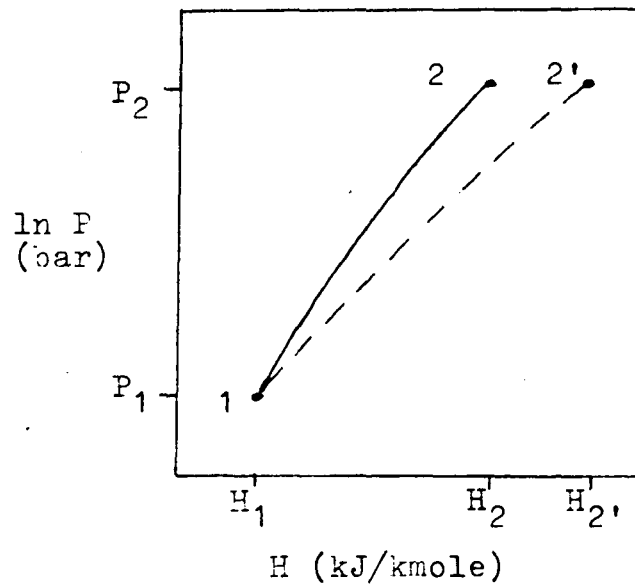


Fig. A.2 P-H Diagram for Compression



allow for compressor irreversibility, this change in enthalpy $(H_2 - H_1)$ is divided by the efficiency assumed, 85% in the base case. This results in a real compression path of the dashed line 1-2'. The compressor work requirement is this change in enthalpy $(H_{2'} - H_1)$ times the flow rate of gas through it, and is greater than for reversible compression. The program then calculates the enthalpy $(H_{2'})$ and the temperature of the exiting stream.

Appendix B.

1. Program Listings and Flowcharts

The glossary, listing, and flowchart are included for the following routines:

Program GAST	Gas Turbine Program
Subroutine HTS	High Temperature Side
Subroutine LTS	Low Temperature Side
Subroutine DPTR	Dew Point Temperature

The remaining routines are the same as those of Dayan et. al.⁴ and may be found listed in their work.

They are:

Subroutine BPTR	Bubble point temperature
Function CCL	Condenser load (called by both CLR and CTR)
Subroutine CLR	Condenser load, Calculates load for given flow and output temperature
Function CP	Specific heat of stream
Subroutine CTR	Condenser temperature. Calculates temperature of outlet stream of an exchanger whose load is specified
Function DHR	Heat of reaction of SO ₃
Subroutine ENTR1	Enthalpy of liquid mixture
Subroutine ENTR2	Enthalpy of gas mixture
Subroutine FINDT	Stream temperature for a given enthalpy
Subroutine HTR	High-temperature (daytime) SO ₃ reactor
Subroutine LHR	Latent heat
Subroutine LTR	Low-temperature (nighttime) SO ₂ reactor
Subroutine RECOPY	Copies data of one record into another
Function TKP	Equilibrium constant in terms of conversion of SO ₃ to SO ₂
Subroutine VKCR	Volatility K constant

PROGRAM GAST

Subroutines Called:

DPTR	Dew point temperature routine
ENTR1	Enthalpy of a liquid mixture
ENTR2	Enthalpy of a gaseous mixture
HTR	High temperature reactor
HTS	High temperature side (daytime process)
LTS	Low temperature side (nighttime process)
RECOPY	Recopy one record to another

Glossary of Variables Used:

ACW	Additional Compressor work
C	Conversion in reactor (HTS)
CEFF	Compressor efficiency
COMPW	Compressor (HTS)
COMPWL	Compressor (LTS)
CONDA	Condenser
CONDB	Condenser
COND1L	Condenser
COND2L	Condenser
COND13	Condenser
DF	Difference in flow between 42 and 1.
DHTP	Increment of HTP for parameter study
DTD56	Delta temp. between streams 5 and 6.
DTMIN	Increment of TMIN for parameter study
DTWMAX	Increment of TWMAX for parameters study
DX	Difference in X_2 of 42 and 1
DX ₂	Increment in X_2 for stream 21.
EFFIC	Efficiency of process
EPSF	Convergence limit for flow
EPSFS	EPSF for stream 5
EPSTS	Convergence limit for T(5)
EPSX	Convergency limit for composition
F	Flow array (kmole/sec)
FC	Final conversion in reactor (LTS)
F11	First guess of F(1)
GCH	Gamma (CP/CV) across compressor (HTS)
GCL	Gamma (CP/CV) across compressor (LTS)
GEH	Gamma (Cp/CV) across turbine (HTS)
GEL	Gamma (Cp/Cv) across turbine (LTS)
GTW	Gas-turbine output (HTS)
GTWL	Gas-turbine output (LTS)
H	Enthalpy array (kmoles/kmole)
HE1L-HE4L	Heat exchangers 1-4
HTP	High pressure for HTS
I, J, K, L, H, N	DO-loop indices
IFP	Indicator for printing

IT, KO	DO-loop indices
LTP	High pressure for LTS
MT	Number of TMIN's for parameter study
NCI	NO convergence indicator
NP	Number of HTP for parameter study
NTW	Number of TWMAX for parameter study
OAC1	Overall Condenser 1
OAC2	Overall condenser 2
OUTD	Net electrical output (daytime)
OUTN	Net electrical output (nighttime)
P	Pressure array (bar)
PA	Pressure array
PRT	Pressure ratio across turbine
QAAN	Heat liberated from reactors at night
R	Ratio for 230 MW receiver
REC	Receiver (reactor portion)
RH	Total receiver duty (MW)
SO	SOR for previous iteration
SOR	SO ₂ /O ₂ ratio in feed to reactor (LTS)
T	Temperature array (K)
TEFF	Turbine efficiency
TMA	TMIN array
TMIN	Minimum temperature in system (k)
TQA	Heat absorbed by HE-1 and Receiver
TRIML	Trimmer (LTS)
TRIM1L	Trimmer 1 (HTS)
TRIM2L	Trimmer 2 (HTS)
TSOURCE	Source temperature at receiver
TWA	TWMAX array
TWMAX	Maximum tube wall temp (K)
VAPR	Vaporizer (LTS)
VAP1L	Vaporizer 1 (HTS)
VAP2L	Vaporizer 2 (HTS)
WR	Work ratio (day/night)
X1	Mole fraction O ₂
X2	Mole fraction SO ₂
X3	Mole fraction SO ₃
X21	Mole fraction SO ₂ in stream 1


```

PROGRAM GAST (INPUT,OUTPUT,PUNCH)
*****
* 6/6/70
* GAST - GAS TURBINE PROCESS FOR CHEMICAL STORAGE OF SOLAR ENERGY. *
*****
*
* PROGRAM CALCULATES A MATERIAL AND ENERGY BALANCE FOR A PROCESS TO
* STORE THERMAL ENERGY CHEMICALLY WHILE PRODUCING ELECTRICITY. THIS PRO
* CESS USES THE CENTRAL RECEIVER CONCEPT FOR SOLAR ENERGY.
* PROGRAM READS IN THE FIRST ESTIMATES FOR STREAM PROPERTIES, THEN
* ITERATES ON THE HTS (DAYTIME) AND LTS (NIGHTTIME PROPERTIES UNTIL THEY
* MATCH. FLOWS AND HEAT DUTIES ARE RATIOED TO A 230 MW RECEIVER AND PRIN
* T-TEMP.
*****
*
REAL LTP
COMMON/STREAM/F(45),P(45),T(45),H(45),X1(45),X2(45),X3(45)
COMMON/LTV/QAAN,ACW,FC,GTWL,COMPWL,GEL,GCL
COMMON/LAHTV/TMIN,HTP,LTP,TEFF,CEFF
COMMON/HTV/EPST5,EPSE5,DTD56,TWMAX,GTW,COMPW,C,TSOURCE,GEH,GCH,PRT
COMMON/HTHEL/COND1L,COND2L,QAC1,QAC2,VAP1L,HE1L,TRIM1L,TRIM2L,COND
1A,CONDB,COND13
COMMON/LTHEL/HE2L,HE3L,HE4L,VAP2L,TRIML
DIMENSION PA(10),TWA(10),TMA(10)
DATA F(45),P(45),T(45),H(45),X1(45),X2(45),X3(45)/7*0./
DATA EPSE5,EPSE5/C,0.005,0.001/
*READ DATA
READ 1,F11,X21
READ 1,HTP,LTP,TEFF,CEFF
READ 1,DTD56,TWMAX,TMIN
READ 1,EPST5,EPSE5
READ 2,DTMIN,TQA
READ 2,DHTP,DTWMAX
READ 13,IT,MT,NTW,NTW
*PRINT INPUT
PRINT 9
PRINT 2,F11,X21, DTD56,TWMAX,TMIN,EPST5,EPSE5,DTMIN,
1TQA,HTP,LTP,IT,MT,NTW,DHTP,NTW,DTWMAX
PRINT 16,TEFF,CEFF
NCI=0
PA(1)=HTP
TWA(1)=TWMAX
TMA(1)=TMIN
DO 14 K=2,10
PA(K)=PA(K-1)+DHTP
TWA(K)=TWA(K-1)+DTWMAX
14 TMA(K)=TMA(K-1)+DTMIN
*START CALCULATIONS - DO LOOPS FOR PARAMETER STUDIES
DO 10 K=1,NTW
DO 10 L=1,NTW
DO 10 M=1,MT
HTP=PA(K)

```

```

      TWMAX=TWA(L)
      TMIN=TMA(V)
*ZERO UNUSED PORTION OF STREAM TABLE
      DO 18 I=1,44
      18 CALL RECOPY(45,I)
*COMPLETE DATA FOR 1 , ASSUME (5)=(1) INITIALLY
      F(1)=F11
      X2(1)=X21
      T(1)=TMIN
      CALL ENTR1(T(1),X2(1),H(1))
      X1(1)=0.
      X3(1)=1.-X2(1)
      P(1)=HTP
      CALL RECOPY(1,5)
      T(5)=TWMAX-DTD56-10.
      CALL ENTR2(T(5),X2(5),X3(5),H(5))
      PRT=16.
*DO-LOOP TO CONVERGE ON DAY-NIGHT BALANCE
      DO 7 I=1,11
      CALL HTJ
*SET UP FOR LOW TEMP. SIDE AND CALL LTS
      CALL RECOPY(17,21)
      CALL RECOPY(15,23)
      P(21)=LTP
      P(23)=LTP
      SO=0.
*DO-LOOP TO SET SO2 RATIO IN LTS STREAM
      DO 38 KO=1,10
      CALL LTS
      SOR=X2(27)/X1(27)
      IF(ABS(SO-SOR).LE..005)GO TO 37
      IF(SOR-1.9) 36,37,37
36 DX2=.005
      IF(1.LT.4) DX2=.010
      X2(21)=X2(21)+DX2
      X3(21)=1.-X2(21)
      SO=SOP
38 CONTINUE
      PRINT 39
39 FORMAT(/3X,*NO CONVERGENCE ON SO2 RATIO*)
*
*F(36) ON LTS IS TESTED TO ENSURE VAPORIZATION IS COMPLETE BY A SMALL
*AMOUNT OF CONDENSATE. IF NOT, P RATIO ADJUSTED.
37 IF(F(36).LE..03) GO TO 45
      PRT=PRT-0.15
      PRINT 43, PRT
43 FORMAT(1X,*PRT= *,F5.2)
      GO TO 19
*CHECK IF MATERIAL BALANCE CLOSES
45 DF=ABS(F(42)-F(1))
      DX=ABS(X2(42)-X2(1))
      IF(DF-EPSE)20,20,19
20 IF(DX-EPSE)24,24,19
34 IF(ABS(F(5)-F(4))-0.002)21,21,19
*SET UP FOR HIGH TEMP. SIDE
19 CALL RECOPY(42,1)
      IF(F(1))21,21,20

```

```

31 PRINT 30,TMIN
   I=IT
   GO TO 10
29 D(1)=HTP
   F(5)=F(1)+F(11)
   X2(5)=(F(1)*X2(1)+F(11)*X2(11))/F(5)
   X3(5)=1.-X2(5)
   7 CONTINUE
*SET NO CONVERGENCE INDICATOR.
   NCI=1
*UPDATE FOR FINAL F(5) AND T(5)
   21 IFD=1
   CALL HTR(F(5),T(5),P(5),X2(5),F(6),T(6),P(6),X1(6),X2(6),X3(6),C,
   ITW,IFP,TSCJRCE)
*SCALE FOR TOTAL RECEIVER= 230. MW AND PRINT
   R=230.E3/(TQA+HE1L+VAP1L)
   DO 15 N=1,44
   F(N)=F(N)*R
15 CONTINUE
   COND1L=COND1L*R
   COND2L=COND2L*R
   OAC1=OAC1*R
   OAC2=OAC2*R
   VAP1L=VAP1L*R
   HE1L=HE1L*R
   CONDA=CONDA*R
   CONDB=CONDB*R
   COND13=COND13*R
   TRIM1L=TRIM1L*R
   TRIM2L=TRIM2L*R
   GTW=GTW*R
   COMPW=COMPW*R
   RH=TQA*R
   VAP2L=VAP2L*R
   HE2L=HE2L*R
   HE3L=HE3L*R
   HE4L=HE4L*R
   TRIML=TRIML*R
   GTWL=GTWL*R
   COMPWL=COMPWL*R
   ACW=ACW*R
   QAAW=QAAW*R
   EFFIC=((GTW-COMPW)+(GTWL-COMPWL-ACW))/(RH +HE1L+VAP1L)
   WR=(GTW-COMPW)/(GTWL-COMPWL-ACW)
   PRINT 17
   IF(NCI.EQ.0) GO TO 25
   PRINT 22,DF,DX
   NCI=0
25 PRINT 11,TMIN,TWMAX,HTP
   PRINT 40
   PRINT 41
   PRINT 42
   PRINT 54,(J),F(J),P(J),T(J),H(J),X1(J),X2(J),X3(J),J=1,20)
   PRINT 54,(J),F(J),P(J),T(J),H(J),X1(J),X2(J),X3(J),J=43,45)
   PRINT 4,COND1L,COND2L,OAC1,OAC2,VAP1L,HE1L,TRIM1L,TRIM2L
   PRINT 35,CONDA,CONDB,COND13
   PRINT 26,GCH,GCH

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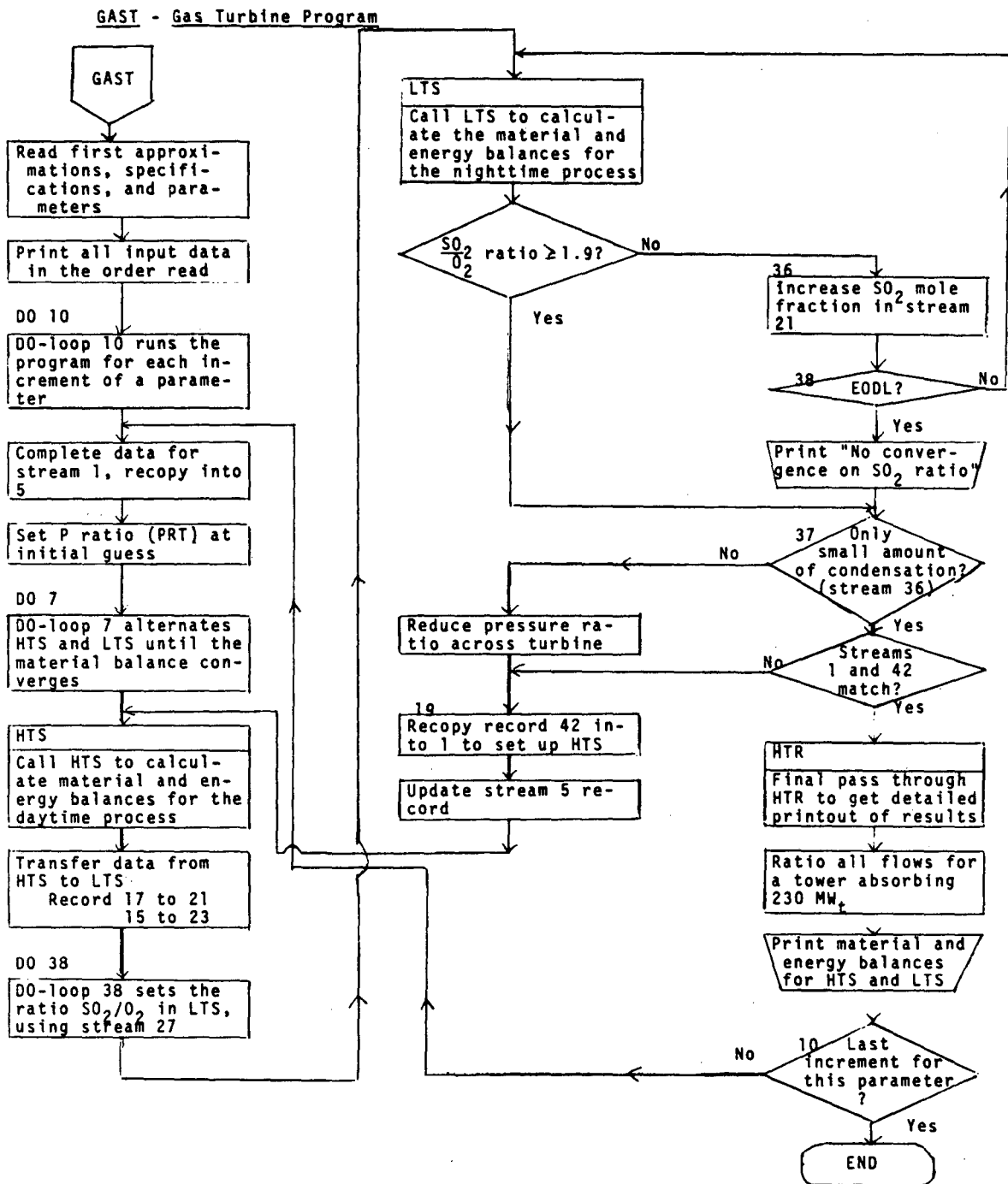
PRINT 27,TSOURCE,C
PRINT 28,RH,HE1L,VAP1L
REC=.001*(RH+HE1L)
VAPR=.001*VAP1L
PRINT 3,RFC,VAPR
PRINT 23,GTW,COMPW
OUTD=.001*(GTW-COMPW)
PRINT 24,OUTD
PRINT 53
PRINT 4
PRINT 4?
PRINT 5,(J,F(J),P(J),T(J),H(J),X1(J),X2(J),X3(J),J=21,42)
PRINT 6,VAP2L,HE2L,HE3L,HE4L,TR1ML
PRINT 26,GEL,GCL
PRINT 5,GTWL,COMPWL,ACW
OUTN=.001*(GTWL-COMPWL-ACW)
PRINT 27,OUTN
PRINT 8,FC,GAAW
PRINT 12,EFFIC,WR
CALL DPTR(12,13,14,T(13))
CALL DPTR(24,25,26,T(25))
10 CONTINUE
*FORMAT STATEMENTS
1 FORMAT(10X,10F10.3)
2 FORMAT(10X,10F10.4)
30FORMAT(/3X,*STREAM 1 INPUT DATA F(1),X2(1)          *,2F10.3,
1      /3X,*PRESCRIBED TEMPS DT056, TWMAX, TMIN        *,3F10.3,
2      /3X,*CONVERGENCE LIMITS EPST5, EPSF5           *,2F10.3,
3      /3X,*PRESCRIBED HEAT LOADS DTMIN, TQA          *,2F10.4,
4      /3X,*HI+LO T PRESS HTP, LTP                   *,2F10.3,
5      /3X,*ITERATIONS+MIN TSS IT, MT                 *,2I10,
6      /3X,*NP, DHTP, NTW, DTWMAX                     *,2(I2,F10.3))
4 FORMAT(/3X,*EXCHANGERS HEAT LOADS COND1L=*,E10.4,3X,*COND2L=*,E10
1.4,2X,*OAC1=*,E10.4,/26X,*OAC2=*,E10.4,5X,*VAP1L=*,F10.4,
2      /26X,*HE1L=*,E10.4,5X,*TR1ML=*,E10.4,3
3X,*TR1M2L=*,E10.4)
5 FORMAT(/3X,*WORK DATA GTW=*,E10.4,*(KW-TH) COMPW=*,E10.4,*KW
1*,3X,*ACW=*,E10.4,2HKW)
60FORMAT(/3X,*EXCHANGERS HEAT LOADS VAP2L=*,F10.4,2X,*HE2L =*,E10.4,
13X,*HE3L=*,E10.3,3X,/25X,*HE4L=*,E10.4,4X,*TR1VL=*,F10.4)
8 FORMAT(/3X,*LOW TEMP. REACTOR RESULTS FC=*,E10.4,3X,*GAAW=*,E10.4
1,3X)
9 FORMAT(/H1,2X,*MATERIAL AND ENERGY BALANCE FOR GAS TURBINE SETUP*/
13X,*INPJT DATA*)
11 FORMAT(3X,*TMIN=*,F5.1,3X,*TMAX=*,F6.1,3X,*HTP=*,F4.1)
12 FORMAT(/3X,*SECOND LAW EFFICIENCY=*,F6.4,3X,*WORK RATIO CHARGE/DI
1SCHARGE=*,F6.3)
13 FORMAT(10X,7I10)
16 FORMAT(/3X,*TURBINE EFFICIENCY = *,F4.3,/3X,*COMPRESSOR EFFICIEN
1CY= *,F4.3)
17 FORMAT(/H1,2X,*BALANCES SCALED FOR 230. MW RECEIVER *)
22 FORMAT(3X,*MATERIAL BALANCE DIDNT CONVERGE. DF=*,E10.4,3X,3HDX=,E1
10.4)
23 FORMAT(/3X,*WORK DATA GTW=*,F10.4,*(KW-TH) COMPW=*,E10.4,*KW*)
24 FORMAT(/3X,*NET DAYTIME WRK OUTPUT= *,F5.1,*(VA)*)
26 FORMAT(/3X,*GMAE=*,F5.3,3X,*GMAC=*,F5.3)
27 FORMAT(3X,*SOURCE TEMP.=*,F6.1,3X,*CONVERSION=*,F5.3)

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28 FORMAT(3X,*HEAT INPUT. REACTOR=*,E10.4,3X,*HEATER=*,E10.4,3X,*VAPO
RIZER=*,E10.4)
30 FORMAT(3X,*F(36)=F(1)=0. NO CONDENSATION AT TMIN=*,F5.1,* GO TO NE
XT *MAX*)
32 FORMAT(/3X,*NET NIGHTTIME WORK OUTPUT= *,F5.1,* (MW)*)
33 FORMAT(/3X,*TOTAL THERMAL INPUTS. RECEIVER= *,F5.1,* (MW),/25X,
1*VAPORIZER= *,F5.1,* (MW)*)
35 FORMAT(/3X,*OTHER EXCHANGERS (KW) *,/5X,*CONDA= *,E10.4,/5X,*CONDB
1= *,E10.4,/5X,*COND13=*,E10.4)
400FORMAT(/3X,*TABLE 1- STREAM DATA FOR THE CHARGE MODE - HIGH TEMPER
ATURE SIDE*)
410FORMAT(2X,*STREAM FLOW PRESSURE TEMP. ENTHALPY COMPO
SITION (MOLE FRACTION)*)
42 FORMAT(4X,*NO. (KMOL/S) (BAR) (K) (KJ/KMOLE) 02
1 S02 S03*)
530FORMAT(1H,3X,*TABLE 2 - STREAM DATA FOR THE DISCHARGE MODE - LOW
TEMPERATURE SIDE*,/15X,*BASED ON 8 HOUR NIGHT*,/)
54 FORMAT(4X,I2,5X,F4.2,7X,F5.2,6X,F6.1,6X,F7.0,8X,F5.3,4X,F5.3,4X,F5
1.2)
END

```



Subroutine HTSSubroutines Called:

BPTR	Bubble point temperature routine
CLR	Condenser load routine
CP	Heat capacity
CTR	Condenser temperature routine
DPTR	Dew point temperature routine
ENTR-2	Enthalpy of a gaseous mixture
FINDT	Find temperature of stream
HTR	High temperature reactor
LHR	Latent heat routine
Recopy	Recopy one record into another

Glossary of variables used:

A,B,C,D	Variables in Newton-Rphson convergen on F(5), T(5)
CEFF	Compressor efficiency
CEXP	Compressor exponent for stream temperature
COMPW	Compressor
CONDA	Condenser
CONDB	Condenser
COND1L	Condenser
COND2L	Condenser
COND2	Condenser
COND10	Condenser
COND13	Condenser
CPM	Heat capacity
DCOND	Variable to adjust condenser load
DCONDA	Variable to adjust condenser load
DCOOL	Variable to adjust condenser load
DELH1	Adjustment to H across turbine
DELH2	Adjustment to H across compressor
DET,DFS,DTS	Variables in Newton Rephson convergence or F(5), T(5)
DTD56	Delta temperature across streams 5 and 6.
EEXP	Turbine exponent for stream temperature
EPSF5	Convergence limit for F(5)
EPST5	Convergence limit for T(5)
F	Flow array (Kmole/sec)
FC	Final conversion of SO ₂ in reactor
FF, FT	Variables in N-R convergence in F(5), T(5)
F5	Flow of stream 5
GAMAC	Gamma (Cp/Cv) for compressor
GAMAE	Gamma (Cp/Cv) for turbine
GTW	Gas turbine output
H	Enthalpy array (kJ/kmole)
Hell	Heat exchanger 1 load
HTP	High pressure (HTS)
HVAP	Enthalpy of saturated vapor (SO ₂)

I,K,L	DO-loop indices
IFP	Indicator for printing
LH3	Latent heat of vaporization of stream 3
LTP	High pressure (LTS)
OAC1	Overall condenser 1
OAC2	Overall condenser 2
P	Pressure array (bar)
PRAT	Pressure ratio across turbine
RAT	Ratio of SO ₂ /O ₂ in material stored
T	Temperature array (K)
TCOND	Condenser
TE	Average temperature in expansion
TEFF	Turbine efficiency
TMIN	Minimum system temperature (K)
THP	THIN + 10 ⁰ K
TRIM1L	Trimmer 1. duty
TRIM2L	Trimmer 2. duty
TSOURCE	Source temperature in receiver
TVAP	Temperature of saturated SO ₃ vapor
TW,TWF,TWT	Variables in N-R convergence on F(5), T(5)
TWMAX	Maximum tube wall temperature (K)
T5, T6F, T6T	Variables in N-R convergence of F(5), T(5)
VAP	Vaporizer load variable
VAPIL	Vaporizer load variable
X1	Mole fraction O ₂
X2	Mole fraction SO ₂
X3	Mole fraction SO ₃

SUBROUTINE HTS

```

*****
*
*   5/9/79
*   HTS - HIGH TEMPERATURE SIDE (DAYTIME PROCESS).
*
*****
*   HTS CONVERGES ON THE RECEIVER-REACTOR FLOWS AND TEMPS, THEN COM-
*   PLETES THE HEAT AND MATERIAL BALANCE BASED ON THIS REACTOR.
*****
*
  REAL LH3,LTP
  COMMON/STREAM/F(45),P(45),T(45),H(45),X1(45),X2(45),X3(45)
  COMMON/LAHTV/TMIN,HTP,LTP      ,TEFF,CEFF
  COMMON/HTV/EPST5,EPST5,DTD56,TWMAX,GTW,COMPW,FC, TSOURCE,GAMAE,GAM
  1AC,PR4T
  COMMON/HTEL/COND1L,COND2L,OAC1,OAC2,VAR1L,HE1L,TRIM1L,TRIM2L,COND
  1A,COND3,COND13
  COND13=0.
*
*DO-LOOP TO SET SO2 RATIO. THIS GIVES FIRST APPROXIMATION, WHICH IS
*FURTHER REFINED BY MAIN PROGRAM GAST.
  DO 20 K=1,5
  PRINT 1
  1 FORVAT(3X,'HTS - MATERIAL AND ENERGY BALANCES -SSS-')
*NEWTON-RAPHSON TECHNIQUE IS USED TO SEARCH FOR F(5) AND T(5).
*SUPPRESS TABLE PRINTING
  IFP=0
*
  DO 60 I=1,10
  F5=F(5)+0.5
  T5=T(5)+2.
  CALL HTR(F(5),T(5),P(5),X2(5),F(6),T(5),P(6),X1(6),X2(6),X3(6),FC,
  1TW,IFP,TSOURCE)
  CALL HTR(F5, T(5),P(5),X2(5),F(5),T5F, P(6),X1(6),X2(6),X3(6),FC,
  1TW5,IFP,TSOURCE)
  CALL HTR(F(5),T5, P(5),X2(5),F(6),T6T, P(6),X1(6),X2(6),X3(6),FC,
  1TW6,IFP,TSOURCE)
  FF=TW-TWMAX
  FT=T(6)-T(5)-DTD56
  A=(TW5-TW)/0.5
  B=(T5T-T5)/2.
  C=(T6F-T(6))/0.5
  D=(T6T-T(6))/2.-1.
  DET=A*D-B*C
  DF5=(FF*D-T*B)/DET
  DT5=(FT*A-FF*C)/DET
  F(5)=F(5)-DF5
  T(5)=T(5)-DT5
  IF (ABS(DF5)-EPST5)61,61,60
  61 IF (ABS(DT5)-EPST5)62,62,60
  60 CONTINUE

```

```

*IF LOOP COMPLETED NO CONVERGENCE ACHIEVED. PRINT MESSAGE.
  PRINT 6,
  64 FORMAT(/3X,*NO CONVERGENCE ON F(5) AND T(5).*)
*LEAVE FOR FINAL F(5) AND T(5)
  62 CALL HT:(F(5),T(5),P(5),X2(5),F(6),T(6),P(6),X1(6),X2(6),X3(6),FC,
  1TW,IFP,TSOURCE)
  X2(5)=1.-X2(5)
  CALL ENTR2(T(5),X2(5),X3(5),H(5))
  CALL ENTR2(T(6),X2(6),X3(6),H(6))
*FIND SO2/O2 RATIO FOR STREAM 10
  CALL RECOPY(6,9)
  P(9)=HTP/PRAT
  T(9)=TMIN+200.
  CALL ENTR2(T(9),X2(9),X3(9),H(9))
  T(10)=TMIN
  CALL CLR(9,10,11,COND10)
  RAT=X2(10)/X1(10)
  IF(RAT-1.25) 15,15,16
  15 X2(5)=X2(5)+C.05
  GO TO 20
  16 IF(RAT-2.20) 17,18,18
  17 X2(5)=X2(5)+.01
  20 CONTINUE
  PRINT 19
  10 FORMAT(/5X,*NO CONVERGENCE ON X2(5)... ..*)
  18 CALL RECOPY(5,18)
  H(19)=(F(1)*H(1)+F(11)*H(11))/F(19)
  T(19)=TMIN
  DO 2 I=2,4
  CALL RECOPY(18,I)
  2 CONTINUE
  CALL RPTR(P(2),X2(2),T(2))
*CALC. HEAT LOAD TO HEAT STREAM 2 FROM STORAGE TO ITS BUBBLE TEMP.
  T(3)=T(2)
  CALL LNTR2(T(3),X2(3),X3(3),H(3))
  CALL LHR(T(3),X2(3),LH3)
  H(2)=H(3)-LH3
  HVAP=H(3)
  TVAP=T(2)+10.
  COND1L=F(2)*(H(2)-H(18))
*(AS TURBINE EXPANSION F(6) TO F(7). FIRST EST. T(7)=T(2)+300.
  CALL RECOPY(6,7)
  T(7)=T(2)+300.
  6 CALL ENTR2(T(7),X2(7),X3(7),H(7))
  TE=(T(6)+T(7))/2.
  CPV=CP(TE,X1(6),X2(6),X3(6))
  GAMAE=CPM/(CPV-2.)
  FEXP=GAMAE/(GAMAE-1.)
  P(7)=P(6)*(T(7)/T(6))**FEXP
  IF(P(7)-P(6)/PRAT+.05) 4,5,5
  4 P(7)=P(6)/PRAT
  T(7)=T(6)/(PRAT)**(1./FEXP)
  GO TO 6
  5 DELH1=H(6)-H(7)
  H(7)=H(6)-DELH1*TEFF
  CALL FINDT(2,7)
  GTW=F(7)*(H(6)-H(7))

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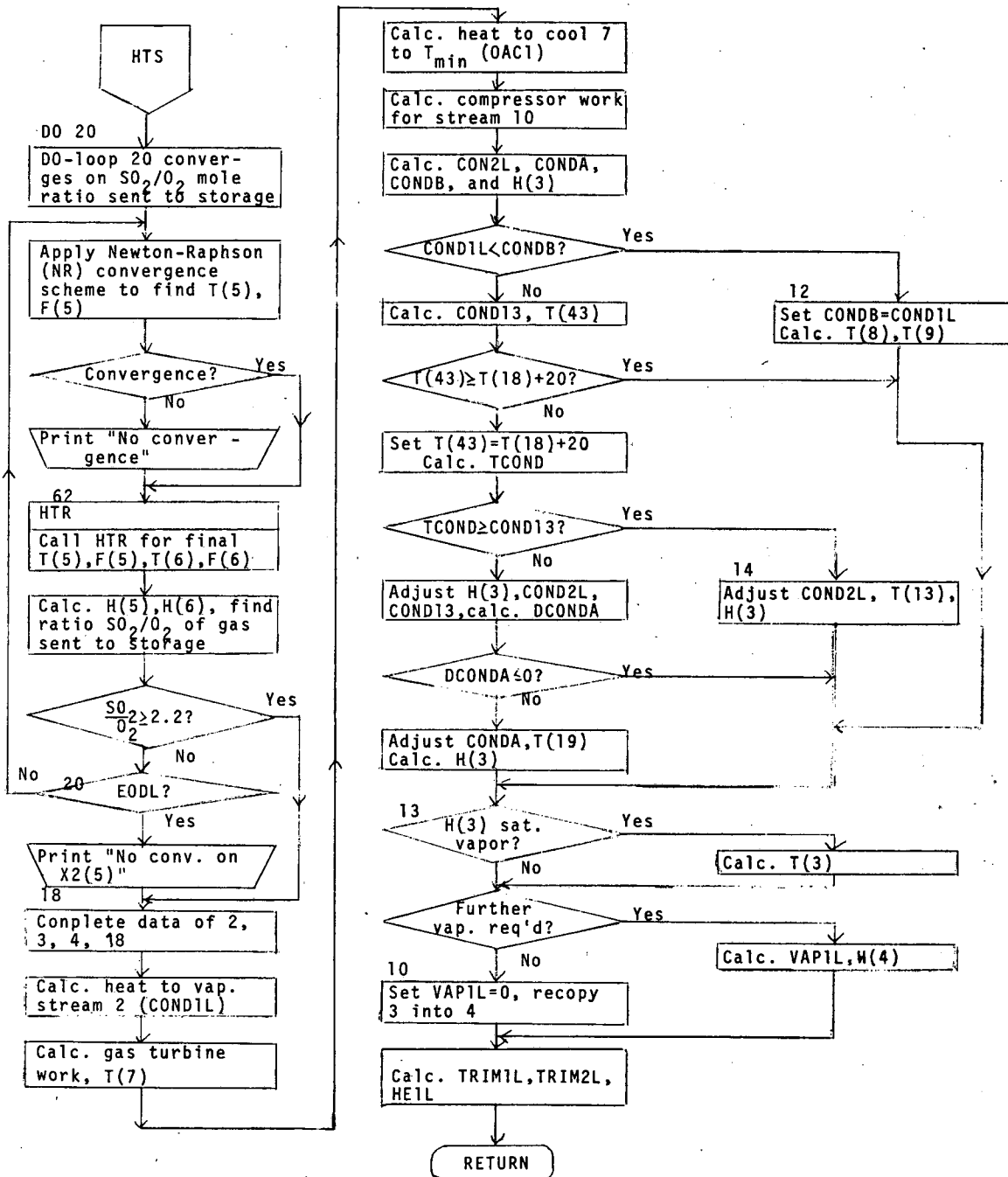
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*STREAM 7 CONDENSATION AND SEPARATION
  T(10)=TMIN
  CALL CLR(7,10,11,OAC1)
*F(12) CONDS. AND COMPRESSOR WORK
  CALL DECOP(10,12)
  P(12)=LIP
  L=0
  T(12)=550.
  7 TE=(T(12)+T(10))/2.
  CPM=CP(TE,X1(10),X2(10),X3(10))
  GAMAC=CPM/(CPV-2.)
  CEXD=(GAMAC-1.)/GAMAC
  T(12)=T(10)*(P(12)/P(10))**CEXD
  IF(L.EQ.7) GO TO 8
  L=L+1
  GO TO 7
  8 CALL ENR2(10,12,12,12,12,H,12)
  DELH2=H(12)-H(10)
  H(12)=DELH2/CEFF+H(10)
  CALL FINDT(2,12)
  COMPW=F(12)*(H(12)-H(10))
*CALC. REMAINING EXCHANGER DUTIES. THEY ARE ADJUSTED TO REFLECT THE A-
*AVAILABILITY OF HEAT IN THE COOLING STREAMS.
  TMD=TMIN+10.
  T(13)=TVAP
  CALL CLR(12,13,14,COND2L)
  T(19)=TVAP
  CALL CLR(7,19,20,CONDA)
  H(3)=H(2)+(CONDA+COND2L)/F(3)
  CALL DPTR(7,8,9,T(8))
  IF(T(8).LT.TMD) T(8)=TMD
  CALL CLR(19,8,9,CONDB)
  IF(COND1L.LT.CONDB) GO TO 12
  COND12=COND1L-CONDB
  CALL CTR(13,43,44,COND12)
  IF(T(43).GE.T(18)+20.) GO TO 12
  T(43)=T(18)+20.
  CALL CLR(12,43,44,TCOND)
  IF(TCOND.GE.COND12) GO TO 14
  DCOOL=COND12-TCOND
  H(3)=H(3)-(COND2L+DCOOL)/F(3)
  COND2L=0.
  COND12=TCOND
  CALL DECOPY(12,12)
  DCONDA=COND1L-COND12-CONDB
  IF(DCONDA.LE.0.) GO TO 13
  CONDA=CONDA-DCONDA
  CALL CTR(7,19,20,CONDA)
  H(3)=H(3)-DCONDA/F(3)
  GO TO 13
  14 COND2=COND2L
  COND2L=TCOND-COND12
  CALL CTR(12,13,14,COND2L)
  DCOND=COND2-COND2L
  H(3)=H(3)-DCOND/F(3)
  GO TO 13
  12 CONDB=COND1L

```

```
CALL CTR(19,8,9,CONDB)
13 IF(H(3).GT.HVAP) CALL FINDT(2,3)
VAP=HVAP-H(2)
IF(VAP.LT.0.) GO TO 10
VAP1L=VAP*F(3)
CALL RECOPY(3,4)
H(4)=HVAP
GO TO 11
10 VAP1L=0.
CALL RECOPY(3,4)
11 CONTINUE
T(15)=TMIN
TR111L=OAC1-CONDA-CONDB
CALL CLR(12,15,16,OAC2)
TR112L=OAC2-COND2L-COND13
*CALC. STREAM 17
CALL RECOPY(16,17)
*CALC. HE1L. ASS STREAM 5 IS KNOWN
HE1L=F(5)*(H(5)-H(4))
*
RETURN
END
```

HTS - High Temperature Side Routine



Subroutine LTSSubroutines Called:

BPTR	Bubble point temperature routine
CLR	Condenser load routine
CP	Heat capacity
CTR	Condenser temperature routine
ENTR2	Enthalpy of a gaseous mixture
FINDT	Find temperature of a stream
LTR	Low temperature reactor
RECOPY	Recopy one record into another

Glossary of variables used:

ACW	Oxygen compressor from storage (C-2)
CEFF	Compressor efficiency
CEXP	Compressor exponent for stream temperature
COMPWL	Recycle compressor (C-1)
CPM	Heat capacity
DELH1	Adjustment to H across compressor
DELH2	Adjustment to H across turbine
DELH3	Adjustment to H across compressor
EEXP	Turbine exponent for stream temperature
F	Flow array (Kmole/sec)
FC	Final conversion of SO ₂ in reactor.
FC1,FC2,FC3	FC of reactors 1, 2, and 3
F41	F(41)
GAMA	Gamma (Cp/Cv) for compressor 2
GAMAC	Gamma (Cp/Cv) for compressor 1
GAHAE	Gamma (Cp/Cv) for the turbine
GTWL	Gas turbine output
H	Enthalpy array (KJ/km)
HAFR1	Heat liberated in reactor 1
HE2L-HE4L	Heat exchangers 1-4.
HE4A	Heat liberated in reactor 3
HTP	High pressure (HTS)
H23	H(23)
I,K,L	Iteration counters
LTP	High pressure (LTS)
P	Pressure array (bar)
PRAT	Pressure ratio across turbine
QAAN	Total heat liberated by reactors
T	Temperature array (K)
TA	Average temperature across compressor
TE	Average temperature across turbine
TEFF	Turbine efficiency
TMIN	Minimum system temperature (K)
TRIML	Trimmer duty

T23,25	T(23), T(25)
VAP2L	Vaporizer duty
X1	Mole fraction O ₂
X2	Mole fraction SO ₂
X3	Mole fraction SO ₃

```

SUBROUTINE LTS
*****
*      5/9/79
*      LTS - LOW TEMPERATURE SIDE (NIGHTTIME PROCESS)
*****
*
*      LTS CALCULATES THE MATERIAL AND ENERGY BALANCES AS PER THE FEED
*STREAMS SET BY HIS. THE RESULTING FLOW AND COMPOSITION OF THE SO3
*STREAM TO STORAGE IS COMPARED WITH THAT USED BY HTS IN GAST.
*****
*
      REAL LTP
      COMMON/STREAM/F(45),P(45),T(45),H(45),X1(45),X2(45),X3(45)
      COMMON/LIV/GAAN,ACW,FC,STWL,COMPWL,GAMAE,GAMAC
      COMMON/LAFTV/TMIN,HIP,LTP,TEFF,CEFF
      COMMON/LTHEL/HE2L,HE3L,HE4L,VAP2L,TRIML
*ZERO HESS LOADS
      DATA HE2L,HE3L,HE4L,HE4A,AP2L,RIVL,6*0.,
      DRAT=0.05

      PRINT 4
      4 FORMAT(/3X,*LTS - MATERIAL AND ENERGI BALANCE*)
      CALL RECOPY(21,22)
      CALL BPIR(P(22),A2(22),I(22))
      CALL FNTR2(I(22),X2(22),A3(22),H(22))
      VAP2L=F(22)*(H(22)-H(21))
      CALL RECOPY(23,24)
*HEATER MAINTAINS F(23) AT TMIN, SINCE IT DROPS IN TEMPERATURE AS THE
*CHAMBER IS EVACUATED.
      T23=IMIN-100.
      K=0
      20 IA=(T23+T(23))/2.
      CPM=CP(TA,X1(23),X2(23),X3(23))
      GAMA=CPM/(CPM-2.)
      EEXP=GAMA/(GAMA-1.)
      T23=I(23)*(0.05)**(1./EEXP)
      K=K+1
      IF(K.LE.1)GO TO 20
      CALL ENTR2(T23,X2(23),X3(23),H23)
      HE2L=F(23)*(H(23)-H23)/2.
*CALC. WORK REQUIRED FOR PUMPING GAS FROM STORAGE. ASSUME GAS IS
*INITIALLY AT LTP AND END AT ZERO PRESSURE. AVERAGE PRESSURE IN THE
*STORAGE IS LIP/2. GAS IS COMPRESSED BY A FACIOR OF TWO. THIS ESTIMATE
*IS REFINED OFF-LINE TO MAINTAIN A PKESSURE ABOVE ATM.
      CALL RECOPY(24,25)
      16 T25=I(25)
      TA=(T25+I(24))/2.
      CPM=CP(TA,X1(25),X2(25),X3(25))
      GAMA=CPM/(CPM-2.)
      CEXP=(GAMA-1.)/GAMA

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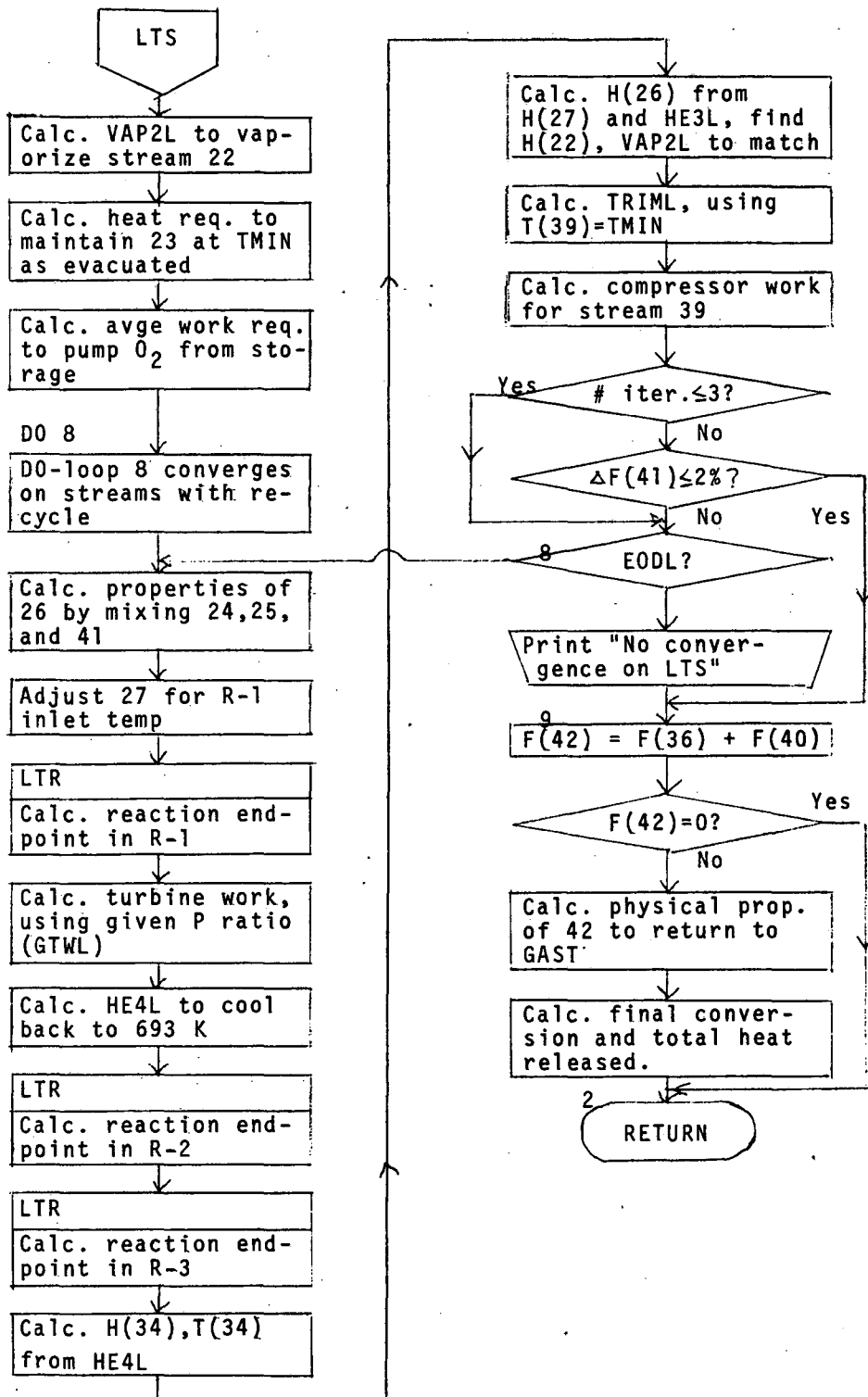
T(25)=T(24)*2.**CEXP
IF(ABS(T25-T(25))-10.)15,15,16
15 CALL ENTR2(T(25),X2(25),X3(25),H(25))
DELH1=H(25)-H(24)
H(25)=DELH1/CEFF+H(24)
CALL FINDT(2,25)
ACW=F(25)*(H(25)-H(24))
DO R I=1,10
*MIX 27,25,41 TO FIND 26
F(26)=F(22)+F(25)+F(41)
H(26)=(F(22)*H(22)+F(25)*H(25)+F(41)*H(41))/F(26)
X2(26)=(F(22)*X2(22)+F(25)*X2(25)+F(41)*X2(41))/F(26)
X3(26)=(F(22)*X3(22)+F(25)*X3(25)+F(41)*X3(41))/F(26)
X1(26)=1.-X2(26)-X3(26)
P(26)=LTP
T(26)=T(22)
CALL FINDT(2,26)
*ADJUST 27 FOR R1 INLET CONDITIONS
CALL RECOPY(26,27)
T(27)=693.
CALL ENTR2(T(27),X2(27),X3(27),H(27))
*CALL REACTOR 1
CALL LTR(FC1,HAFR1,27,28,29)
*TURBINE EXPANSION CALCS.
CALL RECOPY(28,29)
T(29)=693.
P(29)=P(28)*PRAT
L=J
13 TE=(T(28)+T(29))/2.
CPM=CP(TE,X1(29),X2(29),X3(29))
GAMAE=CPM/(CPM-2.)
EEXP=GAMAE/(GAMAE-1.)
T(29)=T(28)*(PRAT)**(1./EEXP)
IF(L.EQ.3)GO TO 12
L=L+1
GO TO 13
12 CALL ENTR2(T(29),X2(29),X3(29),H(29))
DELH2=H(28)-H(29)
H(29)=H(28)-DELH2*TEFF
CALL FINDT(2,29)
GTWL=F(29)*(H(28)-H(29))
*SET INPUT TO R2 , GO THROUGH HE4,R2 AND HE3
CALL RECOPY(29,30)
T(30)=693.
CALL ENTR2(T(30),X2(30),X3(30),H(30))
HE4L=F(30)*(H(30)-H(29))
CALL LTR(FC2,HE3L,30,31,32)
*INPUT TO R3 HAS BEEN ADJUSTED BY LTR USING HE3. GO THROUGH R3
*NOTE THAT HE4A IS HEAT AVAIL. FROM REACTION ONLY . (NOT HE4L)
CALL LTR(FC3,HE4A,32,33,34)
*SUPPLY HEAT NECESSARY IN HE4. AND CALC. 34
H(34)=H(33)-HE4L/F(34)
T(34)=T(29)+10.
CALL FINDT(2,34)
*OC_ 34 THROUGH VAP,HE2,TRIM.,SET T(35) AT T(21)+10. AND T(39) AT TMIN*
H(26)=H(27)-HE3L/F(26)
T(26)=T(27)-(T(31)-T(32))

```

```

CALL FINDT(2,26)
H(22)=(H(26)*F(26)-F(25)*H(25)-F(41)*H(41))/F(22)
T(22)=T(26)
CALL FINDT(2,22)
VAP2L=(H(22)-H(21))*F(22)
T(35)=T(21)+10.
CALL CTR(34,35,36,VAP2L)
T(39)=TMIN
CALL CLR(35,39,40,TRIML)
*COMPRESSING 37 TO 39 AND COMPWORK. CONVERGENCE CHECK BY VALUE OF F(41)*
F41=F(41)
CALL DECOPY(39,41)
P(41)=LTP
T(41)=T(39)*(T(28)/T(29)+1.1)
L=0
25 TE=(T(39)+T(41))/2.
CPM=CP(TE,X1(39),X2(39),X3(39))
GAMAC=CPM/(CPM-2.)
CEXP=(GAMAC-1.)/GAMAC
T(41)=T(39)*(P(41)/P(39))**CEXP
IF(L.EQ.1)GO TO 26
L=1
GO TO 25
26 CALL ENTR2(T(41),X2(41),X3(41),H(41))
DELH3=H(41)-H(39)
H(41)=DELH3/CEFF+H(39)
CALL FINDT(2,41)
COMPWL=(T(39)*(H(41)-H(39)))
* GO THROUGH THREE LOOP CALC. BEFORE CONVERGENCE CHECK.
IF(I.LE.3) GO TO 8
IF(ABS(F41-F(41))-0.02*F(41))>.0.8
8 CONTINUE
PRINT 1J
10 FORMAT(9X,'NO CONVERGENCE ON LTS')
*MIX LIQUID STREAMS 36,38,40 TO FORM 42
0 F(42)=F(36)+F(40)
IF(F(42).EQ.0.) GO TO 2
H(42)=(F(36)*H(36)+F(40)*H(40))/F(42)
X2(42)=(F(36)*X2(36)+F(40)*X2(40))/F(42)
X3(42)=1.-X2(42)
X1(42)=0.
P(42)=HTP
T(42)=(F(36)*T(36)+F(40)*T(40))/F(42)
CALL FINDT(1,42)
* CONVERSION CALCULATIONS - FC. MONITOR HEAT AVAIL. FROM REACTION -QAAN*
FC=(X2(27)-X2(33))/X2(27)/(1.-X2(33)/2.)
QAAN=HAFR1+HE3L+HE4A
2 RETURN
END

```



Subroutine DPTRSubroutines Called:

CLR Condenser load routine

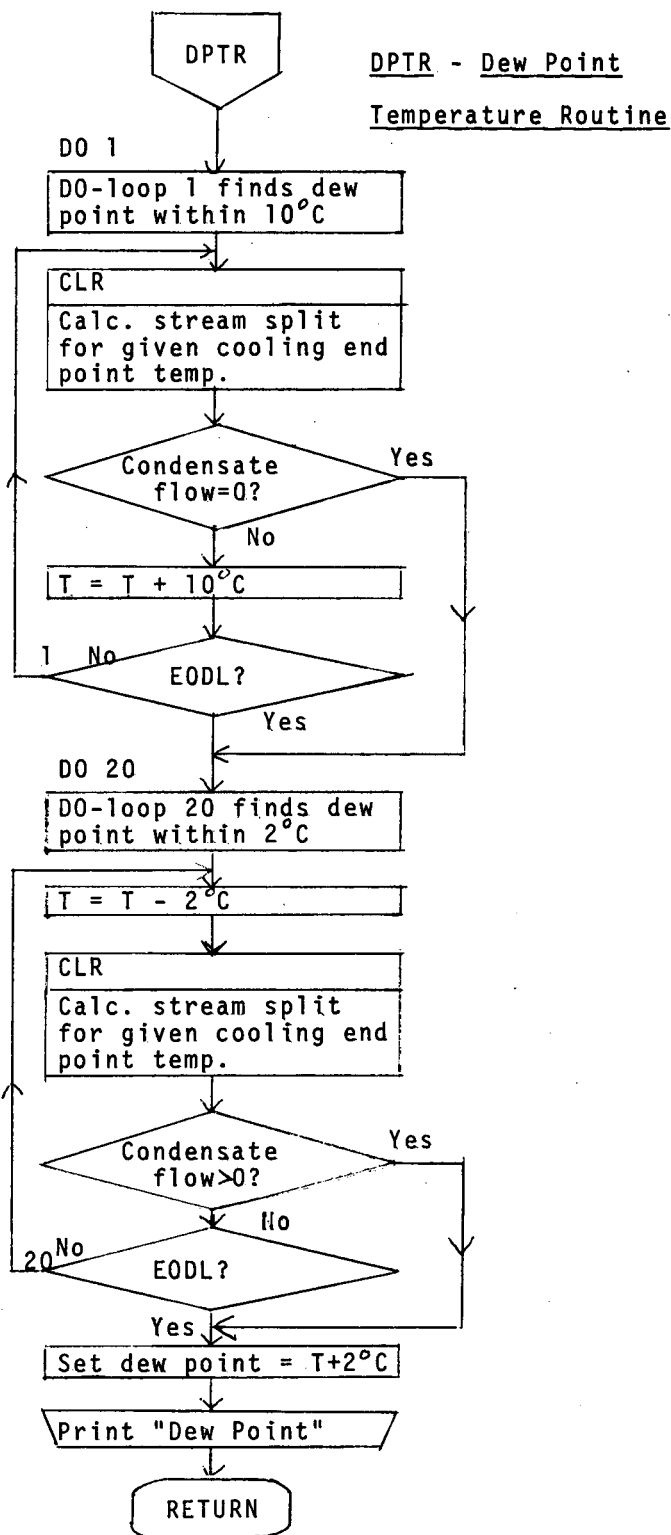
Glossary of variables used:

DPT	Dew point temperature calculated
F	Flow array (Kmole/sec)
I, IN	DO-loop indices
J, K, L	Stream records inputted
T	Temperature array (K)
TESTA	Condenser load
TESTB	Condenser load

```

SUBROUTINE DPTR(J,K,L,DPT)
**** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** **
*           MAY 8, 1979           *
*   DPTR - DEW POINT TEMPERATURE ROUTINE   *
**** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** **
*SUBROUTINE CALCULATES THE DEW POINT OF A CONDENSING STREAM*
**** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** **
COMMON/STREAM/F(45),P(45),T(45),H(45),X1(45),X2(45),X3(45)
T(K)=T(1)
* DO-LOOP INCREASES GUESS OF TEMP. BY 10K; WHEN THERE IS NO CONDENSATE*
*THE FOLLOWING DO-LOOP DECREASES GUESS BY 2K *
DO 1 I=1,10
CALL CLR(J,K,L,TESTA)
IF(F(L).EQ.0.) GO TO 10
T(K)=T(K)+ 10.
1 CONTINUE
10 DO 20 IN=1,10
T(K)=T(K)-2.
CALL CLR(J,K,L,TESTB)
IF(F(L).GT.0.) GO TO 30
20 CONTINUE
30 DPT=T(K)+7.0
PRINT 2, J,DPT
2 FORMAT(1/3X,*DEW POINT OF STREAM *,I2,* IS *,F5.1,* (K)*)
RETURN
END

```



2. Sample Program Printout

The program first prints the input data in the order read. The base case conditions are illustrated here. It then alternates HTS and LTS until the material balance matches.

The results of the high-temperature reactor are then printed, the column headings defined as follows:

NOS	-	Number of section
L	-	Length along the reactor
TW	-	Outside tube wall temperature (K)
TS	-	Temperature of gas at wall (K)
TB	-	Bulk temperature of the gas (K)
Q	-	Total heat absorbed by gas
QR	-	Heat of reaction absorbed
QS	-	Sensible heat absorbed
C	-	Conversion of SO ₃
Y-SO ₃	-	Mole fraction SO ₃
Y-SO ₂	-	Mole fraction SO ₂
Y-O ₂	-	Mole fraction O ₂

The equilibrium conversion of SO₃ at the tube wall is then printed for each section, with the length along the reactor. The final values for the exiting gas (stream 6) are then printed.

The program then prints Table 1, the results for the daytime process, and Table 2, the results for the nighttime process.

Note: Some of the stream number and heat exchanger names are different from those used in the main text.

MATERIAL AND ENERGY BALANCE FOR GAS TURBINE SETUP
INPUT DATA

STREAM 1 INPUT DATA F(1),X2(1)	5.000	.055	
PRESCRIBED TEMPS DTD56, TMAX, TMIN	140.000	1153.000	313.000
CONVERGENCE LIMITS EPST5, EPSF5	.500	.050	
PRESCRIBED HEAT LOADS DTMIN, TQA	.5000E+01	.2300E+06	
HI+LO T PRESS HTP, LTP	40.000	40.000	
ITERATIONS+MIN T'S IT, MT	15	1	
NP, DHTP, NTW, DTWMAX	1	5.000	10.000

TURBINE EFFICIENCY = .900
COMPRESSOR EFFICIENCY = .850

HTS - MATERIAL AND ENERGY BALANCES -\$\$\$-

HTS - MATERIAL AND ENERGY BALANCES -\$\$\$-

HTS - MATERIAL AND ENERGY BALANCES -\$\$\$-

HTS - MATERIAL AND ENERGY BALANCES -\$\$\$-

HTS - MATERIAL AND ENERGY BALANCES -\$\$\$-

NO CONVERGENCE ON X2(5)... ..

DEW POINT OF STREAM 7 IS 323.0 (K)

LTS - MATERIAL AND ENERGY BALANCES
NO CONVERGENCE ON LTS

LTS - MATERIAL AND ENERGY BALANCES

LTS - MATERIAL AND ENERGY BALANCES

LTS - MATERIAL AND ENERGY BALANCES

LTS - MATERIAL AND ENERGY BALANCES

LTS - MATERIAL AND ENERGY BALANCES

LTS - MATERIAL AND ENERGY BALANCES

HTS - MATERIAL AND ENERGY BALANCES -\$\$\$-

DEW POINT OF STREAM 7 IS 323.0 (K)

LTS - MATERIAL AND ENERGY BALANCES

HTS - MATERIAL AND ENERGY BALANCES -\$\$\$-

DEW POINT OF STREAM 7 IS 323.1 (K)

LTS - MATERIAL AND ENERGY BALANCES

HIGH TEMPERATURE REACTOR RESULTS

NDS	L	TW	TS	TR	J	QR	QS	E	Y-S03	Y-S02	Y-02
1	.20	1056.3	1056.1	1006.7	.7194E+03	.3983E+03	.3211E+03	J.	.877	.123	0.
2	.40	1056.5	1058.5	1013.6	.1426E+04	.7941E+03	.5323E+03	.71	.671	.127	.032
3	.60	1068.8	1060.8	1014.5	.2121E+04	.1107E+04	.9139E+03	.61	.865	.131	.004
4	.80	1070.9	1063.1	1018.2	.2804E+04	.1578E+04	.1222E+04	.15	.858	.135	.037
5	1.00	1073.0	1065.3	1021.9	.3476E+04	.1966E+04	.1504E+04	.21	.852	.139	.009
6	1.20	1075.1	1067.5	1025.4	.4135E+04	.2351E+04	.1784E+04	.25	.846	.143	.011
7	1.40	1077.0	1069.6	1028.8	.4784E+04	.2734E+04	.2050E+04	.30	.840	.147	.013
8	1.60	1079.0	1071.7	1032.1	.5422E+04	.3113E+04	.2308E+04	.35	.834	.151	.015
9	1.80	1080.9	1073.7	1035.3	.6049E+04	.3490E+04	.2559E+04	.39	.828	.155	.017
10	2.00	1082.7	1075.6	1038.5	.6665E+04	.3864E+04	.2801E+04	.44	.822	.159	.019
11	2.20	1084.5	1077.5	1041.5	.7271E+04	.4234E+04	.3037E+04	.49	.817	.162	.021
12	2.40	1086.2	1079.4	1044.5	.7867E+04	.4602E+04	.3265E+04	.54	.811	.166	.023
13	2.60	1087.9	1081.2	1047.3	.8453E+04	.4966E+04	.3487E+04	.59	.805	.170	.025
14	2.80	1089.6	1083.0	1050.1	.9029E+04	.5327E+04	.3702E+04	.63	.800	.174	.027
15	3.00	1091.2	1084.7	1052.9	.9596E+04	.5685E+04	.3910E+04	.68	.794	.177	.029
16	3.20	1092.8	1086.4	1055.5	.1015E+05	.6040E+04	.4113E+04	.72	.789	.181	.031
17	3.40	1094.3	1088.0	1058.1	.1070E+05	.6392E+04	.4310E+04	.77	.783	.184	.033
18	3.60	1095.8	1089.7	1060.5	.1124E+05	.6740E+04	.4500E+04	.82	.778	.188	.035
19	3.80	1097.3	1091.2	1063.3	.1177E+05	.7085E+04	.4686E+04	.87	.773	.191	.036
20	4.00	1098.7	1092.8	1065.3	.1229E+05	.7427E+04	.4866E+04	.91	.767	.195	.038
21	4.20	1100.2	1094.3	1067.6	.1281E+05	.7765E+04	.5041E+04	.95	.762	.198	.040
22	4.40	1101.5	1095.7	1069.9	.1331E+05	.8100E+04	.5211E+04	.99	.757	.201	.042
23	4.60	1102.9	1097.2	1072.3	.1381E+05	.8432E+04	.5376E+04	.103	.752	.205	.044
24	4.80	1104.2	1098.6	1074.2	.1430E+05	.8760E+04	.5536E+04	.108	.747	.208	.045
25	5.00	1105.5	1099.9	1076.2	.1478E+05	.9085E+04	.5692E+04	.112	.742	.211	.047
26	5.20	1106.7	1101.3	1078.2	.1525E+05	.9407E+04	.5844E+04	.117	.737	.214	.049
27	5.40	1107.9	1102.6	1080.2	.1572E+05	.9725E+04	.5992E+04	.121	.732	.217	.050
28	5.60	1109.1	1103.9	1082.1	.1618E+05	.1004E+05	.6135E+04	.125	.727	.221	.052
29	5.80	1110.3	1105.1	1083.9	.1663E+05	.1035E+05	.6273E+04	.129	.723	.224	.054
30	6.00	1111.4	1106.3	1085.7	.1707E+05	.1066E+05	.6410E+04	.133	.718	.227	.055
31	6.20	1112.6	1107.5	1087.5	.1751E+05	.1097E+05	.6542E+04	.138	.713	.230	.057
32	6.40	1113.6	1108.7	1089.2	.1794E+05	.1127E+05	.6671E+04	.142	.709	.233	.058
33	6.60	1114.7	1109.9	1090.9	.1836E+05	.1157E+05	.6796E+04	.146	.704	.236	.060
34	6.80	1115.8	1111.0	1092.5	.1878E+05	.1186E+05	.6918E+04	.150	.700	.238	.062
35	7.00	1116.8	1112.1	1094.1	.1919E+05	.1215E+05	.7036E+04	.154	.696	.241	.063
36	7.20	1117.8	1113.2	1095.7	.1959E+05	.1244E+05	.7152E+04	.157	.691	.244	.065
37	7.40	1118.8	1114.2	1097.2	.1999E+05	.1273E+05	.7265E+04	.161	.687	.247	.066
38	7.60	1119.7	1115.3	1098.6	.2038E+05	.1301E+05	.7374E+04	.165	.683	.250	.068
39	7.80	1120.7	1116.3	1100.1	.2077E+05	.1329E+05	.7481E+04	.169	.679	.252	.069
40	8.00	1121.6	1117.3	1101.5	.2115E+05	.1356E+05	.7585E+04	.173	.675	.255	.070
41	8.20	1122.5	1118.2	1102.9	.2152E+05	.1383E+05	.7687E+04	.175	.671	.258	.072
42	8.40	1123.4	1119.2	1104.2	.2189E+05	.1410E+05	.7786E+04	.180	.667	.260	.073
43	8.60	1124.3	1120.1	1105.5	.2225E+05	.1437E+05	.7882E+04	.184	.663	.263	.075
44	8.80	1125.1	1121.0	1106.8	.2261E+05	.1464E+05	.7976E+04	.187	.659	.265	.076
45	9.00	1126.0	1121.9	1108.3	.2296E+05	.1489E+05	.8068E+04	.191	.655	.268	.077
46	9.20	1126.9	1122.8	1109.3	.2331E+05	.1515E+05	.8154E+04	.194	.651	.270	.079
47	9.40	1127.6	1123.7	1110.4	.2365E+05	.1540E+05	.8245E+04	.198	.647	.273	.080
48	9.60	1128.4	1124.5	1111.6	.2399E+05	.1565E+05	.8331E+04	.201	.644	.275	.081
49	9.80	1129.1	1125.3	1112.8	.2432E+05	.1590E+05	.8411E+04	.205	.640	.277	.082
50	10.00	1129.9	1126.2	1113.9	.2464E+05	.1615E+05	.8495E+04	.208	.637	.280	.084
51	10.20	1130.6	1127.0	1115.0	.2496E+05	.1639E+05	.8575E+04	.211	.633	.282	.085
52	10.40	1131.4	1127.7	1116.7	.2528E+05	.1663E+05	.8652E+04	.215	.630	.284	.086
53	10.60	1132.1	1128.5	1117.1	.2559E+05	.1686E+05	.8729E+04	.219	.627	.287	.087
54	10.80	1132.9	1129.3	1117.4	.2590E+05	.1710E+05	.8802E+04	.224	.623	.289	.088
55	11.00	1133.5	1130.0	1117.1	.2620E+05	.1733E+05	.8870E+04	.228	.619	.291	.090
56	11.20	1134.1	1130.7	1117.0	.2650E+05	.1756E+05	.8934E+04	.233	.616	.293	.091
57	11.40	1134.8	1131.4	1117.0	.2679E+05	.1778E+05	.9001E+04	.238	.613	.295	.092
58	11.60	1135.5	1132.1	1117.0	.2708E+05	.1800E+05	.9062E+04	.244	.610	.297	.093

59	11.80	1136.1	1132.8	1122.9	.2737E+05	.1922E+05	.9148E+04	.237	.676	.300	.094
60	12.00	1136.7	1133.5	1123.8	.2765E+05	.1844E+05	.9213E+04	.243	.673	.302	.095
61	12.20	1137.3	1134.2	1124.6	.2793E+05	.1865E+05	.9276E+04	.243	.670	.304	.096
62	12.40	1137.9	1134.8	1125.5	.2820E+05	.1886E+05	.9338E+04	.245	.597	.306	.097
63	12.60	1138.5	1135.5	1126.3	.2847E+05	.1907E+05	.9398E+04	.249	.594	.308	.098
64	12.80	1139.1	1136.1	1127.2	.2873E+05	.1928E+05	.9458E+04	.252	.591	.309	.099
65	13.00	1139.7	1136.7	1128.0	.2899E+05	.1948E+05	.9515E+04	.255	.588	.311	.100
66	13.20	1140.3	1137.3	1128.8	.2925E+05	.1968E+05	.9572E+04	.257	.585	.313	.101
67	13.40	1140.8	1137.9	1129.5	.2951E+05	.1988E+05	.9628E+04	.263	.582	.315	.102
68	13.60	1141.4	1138.5	1130.3	.2976E+05	.2007E+05	.9682E+04	.263	.580	.317	.103
69	13.80	1141.9	1139.1	1131.0	.3000E+05	.2027E+05	.9735E+04	.255	.577	.319	.104
70	14.00	1142.4	1139.6	1131.8	.3024E+05	.2046E+05	.9788E+04	.268	.574	.321	.105
71	14.20	1142.9	1140.2	1132.5	.3048E+05	.2065E+05	.9839E+04	.271	.572	.322	.106
72	14.40	1143.4	1140.7	1133.2	.3072E+05	.2083E+05	.9889E+04	.274	.569	.324	.107
73	14.60	1143.9	1141.3	1133.9	.3095E+05	.2101E+05	.9938E+04	.276	.566	.326	.108
74	14.80	1144.4	1141.8	1134.6	.3118E+05	.2123E+05	.9986E+04	.279	.564	.327	.109
75	15.00	1144.9	1142.3	1135.2	.3141E+05	.2137E+05	.1003E+05	.281	.561	.329	.110
76	15.20	1145.4	1142.8	1135.9	.3163E+05	.2155E+05	.1008E+05	.284	.554	.331	.111
77	15.40	1145.8	1143.3	1136.5	.3185E+05	.2173E+05	.1012E+05	.286	.550	.332	.112
78	15.60	1145.3	1143.8	1137.1	.3207E+05	.2190E+05	.1017E+05	.289	.554	.334	.112
79	15.80	1145.7	1144.3	1137.7	.3228E+05	.2207E+05	.1021E+05	.291	.551	.335	.113
80	16.00	1147.2	1144.8	1138.4	.3249E+05	.2224E+05	.1025E+05	.294	.549	.337	.114
81	16.20	1147.6	1145.2	1138.9	.3270E+05	.2240E+05	.1030E+05	.296	.547	.339	.115
82	16.40	1148.0	1145.7	1139.5	.3290E+05	.2256E+05	.1034E+05	.298	.544	.340	.116
83	16.60	1148.5	1146.2	1140.1	.3310E+05	.2273E+05	.1038E+05	.301	.542	.342	.116
84	16.80	1148.9	1146.6	1140.7	.3330E+05	.2288E+05	.1042E+05	.303	.540	.343	.117
85	17.00	1149.3	1147.0	1141.2	.3350E+05	.2304E+05	.1046E+05	.305	.538	.344	.118
86	17.20	1149.7	1147.5	1141.8	.3369E+05	.2320E+05	.1049E+05	.307	.535	.346	.119
87	17.40	1150.1	1147.9	1142.3	.3388E+05	.2335E+05	.1053E+05	.310	.533	.347	.120
88	17.60	1150.5	1148.3	1142.8	.3407E+05	.2350E+05	.1057E+05	.312	.531	.349	.120
89	17.80	1150.8	1148.7	1143.3	.3425E+05	.2365E+05	.1060E+05	.314	.529	.350	.121
90	18.00	1151.2	1149.1	1143.8	.3444E+05	.2380E+05	.1064E+05	.316	.527	.351	.122
91	18.20	1151.6	1149.5	1144.3	.3462E+05	.2394E+05	.1067E+05	.313	.525	.353	.122
92	18.40	1152.0	1149.9	1144.8	.3479E+05	.2409E+05	.1071E+05	.320	.523	.354	.123
93	18.60	1152.3	1150.3	1145.3	.3497E+05	.2423E+05	.1074E+05	.322	.521	.355	.124
94	18.80	1152.7	1150.7	1145.8	.3514E+05	.2437E+05	.1077E+05	.324	.519	.357	.125
95	19.00	1153.0	1151.1	1146.2	.3531E+05	.2451E+05	.1081E+05	.325	.517	.358	.125
96	19.00	0.	0.	1146.7	0.	0.	0.	.325	.515	.359	.126

THERMAL POWER ABSORBED BY GAS- .2300E+03MW-THERMAL) SOJRCR TEMP.=1176.7(K) DIF=-.2215E-02MW

EQUILIBRIUM CONVERSION IN HTR

.20	.2480	.40	.2524	.60	.2567
.80	.2609	1.00	.2650	1.20	.2690
1.40	.2729	1.60	.2767	1.80	.2805
2.00	.2841	2.20	.2877	2.40	.2912
2.60	.2947	2.80	.2980	3.00	.3015
3.20	.3046	3.40	.3077	3.60	.3108
3.80	.3138	4.00	.3167	4.20	.3192
4.40	.3225	4.60	.3252	4.80	.3279
5.00	.3306	5.20	.3332	5.40	.3357
5.60	.3382	5.80	.3406	5.00	.3430
6.20	.3453	6.40	.3476	5.60	.3499
6.80	.3521	7.00	.3542	7.20	.3563
7.40	.3584	7.60	.3604	7.80	.3624
8.00	.3643	8.20	.3662	8.40	.3681
8.60	.3699	8.80	.3717	9.00	.3734
9.20	.3752	9.40	.3768	9.60	.3785
9.80	.3801	10.00	.3817	10.20	.3832
10.40	.3848	10.60	.3863	10.80	.3875
11.00	.3893	11.20	.3907	11.40	.3921
11.60	.3934	11.80	.3948	12.00	.3961
12.20	.3974	12.40	.3987	12.60	.3999
12.80	.4012	13.00	.4024	13.20	.4046
13.40	.4047	13.60	.4059	13.80	.4077
14.00	.4081	14.20	.4092	14.40	.4102
14.60	.4113	14.80	.4123	15.00	.4132
15.20	.4143	15.40	.4153	15.60	.4163
15.80	.4172	16.00	.4181	16.20	.4190
16.40	.4199	16.60	.4208	16.80	.4217
17.00	.4226	17.20	.4234	17.40	.4242
17.60	.4250	17.80	.4258	18.00	.4260
18.20	.4274	18.40	.4282	18.60	.4285
18.80	.4297	19.00	.4304	19.00	.4304

HTR RETURNS WITH?

F(6)	T(6)	P(6)	X1(6)
7.265	1146.671	40.000	.125

X2(6)	X3(6)	FC	TWM
.359	.517	.325	1153.010

BALANCES SCALED FOR 230. MW RECEIVER
 TMIN=313.0 TMAX=1153.0 HTP=40.0

TABLE 1- STREAM DATA FOR THE CHARGE MODE - HIGH TEMPERATURE SIDE

STREAM NO.	FLOW (KMOL/S)	PRESSURE (BAR)	TEMP. (K)	ENTHALPY (KJ/KMOLE)	COMPOSITION (MOLE FRAC.)		
					S2	S22	S33
1	1.74	40.00	313.1	-39437.	0.	.060	.940
2	3.33	40.00	435.5	-11657.	0.	.123	.877
3	3.33	40.00	555.0	15129.	0.	.123	.877
4	3.33	40.00	555.0	15129.	0.	.123	.877
5	3.33	40.00	1006.7	48053.	0.	.123	.877
6	3.80	40.00	1146.7	50457.	.125	.358	.517
7	3.80	2.50	841.4	30270.	.125	.358	.517
8	3.80	2.50	323.1	1128.	.125	.358	.517
9	0.	0.	323.1	0.	0.	0.	0.
10	2.22	2.50	313.0	617.	.215	.477	.308
11	1.59	2.50	313.0	-36752.	0.	.191	.609
12	2.22	40.00	548.7	11645.	.215	.477	.308
13	2.22	40.00	535.1	11014.	.215	.477	.308
14	0.	0.	536.1	0.	0.	0.	0.
15	.53	40.00	313.0	457.	.897	.093	.010
16	1.69	40.00	313.0	-28379.	0.	.593	.402
17	1.69	40.00	313.0	-28379.	0.	.593	.402
18	3.33	40.00	313.0	-38207.	0.	.123	.877
19	3.80	2.50	445.5	7206.	.125	.358	.517
20	0.	0.	445.5	0.	0.	0.	0.
43	.58	40.00	333.0	1114.	.917	.160	.022
44	1.63	40.00	333.0	-25363.	0.	.590	.410
45	0.	0.	0.	0.	0.	0.	0.

EXCHANGERS HEAT LOADS COND1L=.8836E+05 COND2L=.1400E+04 JAC1=.1721E+06
 JAC2=.7345E+05 VAP1L=0.
 HE1L=.1096E+06 TRIM1L=.6124E+05 TRIM2L=.5911E+04

OTHER EXCHANGERS (KW)
 CONDA=.8774E+05
 CONDB=.2312E+05
 COND13=.6524E+05

GAMAE=1.146 GAMAC=1.219
 SOURCE TEMP.=1176.7 CONVERSION=.326
 HEAT INPUT. REACTOR=.1204E+06 HEATER=.1096E+06 VAPORIZER=0.

TOTAL THERMAL INPUTS. RECEIVER= 230.0 (MW)
 VAPORIZER= 0. (MW)

WRK DATA STW=.7680E+05(KW-TM) COMPW=.2445E+05KW

NET DAYTIME WRK OUTPJT= 52.3 (MW)

TABLE 2 - STREAM DATA FOR THE DISCHARGE MODE - LOW TEMPERATURE SIDE
 BASED ON 8 HOUR NIGHT

STREAM NO.	FLOW (KMDL/S)	PRESSURE (BAR)	TEMP. (K)	ENTHALPY (KJ/KMOLE)	COMPOSITION (MOLE FRAC.)		
					O2	SO2	S73
21	1.69	40.00	313.0	-28379.	0.	.598	.402
22	1.69	40.00	532.0	11839.	0.	.598	.402
23	.53	40.00	313.0	457.	.897	.093	.010
24	.53	40.00	313.0	457.	.897	.093	.010
25	.53	40.00	387.6	2803.	.897	.093	.010
26	2.48	40.00	515.9	10012.	.231	.446	.323
27	2.48	40.00	693.0	19135.	.231	.446	.323
28	2.20	40.00	1045.0	45093.	.134	.250	.616
29	2.20	2.00	750.8	25459.	.134	.250	.616
30	2.20	2.00	693.0	21837.	.134	.250	.616
31	2.08	2.00	851.5	34148.	.082	.146	.771
32	2.08	2.00	693.0	23264.	.082	.146	.771
33	2.00	2.00	790.7	31164.	.048	.077	.875
34	2.00	2.00	845.0	35146.	.048	.077	.875
35	1.99	2.00	327.8	1495.	.048	.077	.875
36	.01	2.00	327.8	-37662.	0.	.016	.984
37	0.	0.	0.	0.	0.	0.	0.
38	0.	0.	0.	0.	0.	0.	0.
39	.26	2.00	313.0	615.	.366	.185	.447
40	1.73	2.00	313.0	-39462.	0.	.060	.940
41	.26	40.00	571.2	12851.	.366	.185	.447
42	1.74	40.00	313.1	-39451.	0.	.060	.940

EXCHANGERS HEAT LOADS VAP2L = .6784E+05 HE2L = .1329E+04 HE3L = .226E+05
 HE4L = -.7974E+04 TRIML = .7110E+05

GAMAE=1.144 GAMAC=1.218

WORK DATA GTW = .4322E+05 (KW-T4) COMPW = .3211E+04 KW ACW = .1245E+04 KW

NET NIGHTTIME WORK OUTPUT = 38.8 (MW)

LOW TEMP. REACTOR RESULTS FC = .8615E+00 QAAN = .8771E+05

SECOND LAW EFFICIENCY = .3961 WORK RATIO CHARGE/DISCHARGE = 1.350

DEW POINT OF STREAM 12 IS 409.1 (K)

DEW POINT OF STREAM 34 IS 329.1 (K)

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