AN ECONOMIC EVALUATION OF A PRESSURE SULFURIC ACID MANUFACTURING PLANT

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FACULTY COMMITTEE

APPROVED: ______________________________

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1970

The author wishes to thank Dr. Deran Hanesian for his guidance in carrying this work to completion. Also, thanks to Miss M. Foernsler for the preparation of the manuscript.

Dedicated with all my love to Mary Frances and a little girl named Kimberly Ann.

ABSTRACT

The production of Sulfuric Acid at elevated pressures is presented with the economics for operating at one, three, five, seven, nine and thirteen atmospheres. The conventional and pressure plants are compared operating on the same basis.

The basis for a pressure plant design is obtained from an I.B.M. 1130 computer program developed for One Thousand Net Tons per Day of Sulfuric Acid. Recognized operating conditions for a conventional acid plant are incorporated in the pressure plant design program.

Sulfuric Acid manufacture with operating pressures higher than atmospheric, but less than five atmospheres, results in maximum rate of return on investment and operating economy.

A compressor and gas expander arrangement can significantly reduce operating costs in a pressure plant without sacrifice to the steam generation capabilities associated with sulfuric acid production.

TABLE OF CONTENTS

	PAGE
Introduction	1
Design of Process	3
Introduction	3
I. Heat and Material Balance	9
II. Equipment Design	10
(1) Converter Design	10
(a) Converter heat balance	15
(b) Converter equilibrium calculation	17
(c) Converter catalyst requirement	19
(d) Converter diameter calculation	23
(e) Converter pressure calculation	24
(2) Absorption and Drying Tower	25
(a) Calculation of tower diameter	27
(b) Calculation of tower height	28
(3) Heat Exchangers	30
(a) Design of gas/gas heat exchangers	30
(a1) Calculation of optimum velocity	31
(a2) Calculation of heat transfer coefficients	33
(a3) Calculation of heat transfer area	33

PAGE

(a4) Calculation of heat exchanger pressure drop 34

(b) Design of gas/liquid heat exchangers 36

(c) Design of liquid/liquid heat exchangers 36

(4) Compressor/Expander 37

(5) Miscellaneous Equipment 41

Basis for Economic Considerations 42

Determination of Total Cost 44

Basis for Economic Comparisons 52

Result of Study 55

Conclusions 63

Recommendations 64

References 65

Nomenclature 67

Appendix 73

A. Sample Calculations 74

B. Computer Programs 80

C. Miscellaneous Information 107

D. Computer Output 110

E. Physical Properties 129

LIST OF TABLES

		PAGE
Table I	Operating Guide lines for a Sulfuric Acid Plant	8
Table II	Field Module Costs	48
Table III	Equipment Design Basis	49
Table IV	Equipment Design Basis	50
Table V	Equipment Design Basis	51
Table VI	Total Manufacturing Cost for Conventional H_2SO_4 Plants - 1000 NT/Day	53
Table VII	Earnings for a Conventional H_2SO_4 Plant - 1000 NT/Day	54
Table VIII	Equipment Design - Computer Results	57
Table IX	Compressor/Expander Characteristics	58
Table X	Equipment Cost	59
Table XI	Fixed Capital vs Pressure	60
Table XII	Economic Evaluations of a Pressure Plant - 1000 NT/Day H_2SO_4	61

LIST OF FIGURES

		PAGE
Figure 1	Conventional Sulfuric Plant	4
Figure 2	Pressure Sulfuric Plant	6
Figure 3	Heat and Material Balance Block Diagram (Sub program M 88)	11
Figure 4	Heat and Material Balance Block Diagram (M 88 continued)	12
Figure 5	Heat and Material Balance Block Diagram - N 88 Sub program	13
Figure 6	Conversion vs Temperature	14
Figure 7	Eklund Data, k * vs T	21
Figure 8	Generalized Pressure Drop Curve for Packed Column	26
Figure 9	Heat Exchanger Block Diagram	35
Figure 10	Compressor/Expander System	39
Figure 11	Total Installed Cost by Module Analysis	45
Figure 12	Rate of Return vs Pressure	62

AN ECONOMIC EVALUATION OF A PRESSURE SULFURIC ACID MANUFACTURING PLANT

INTRODUCTION

The chamber and contact process are the two main procedures used to commercially manufacture sulfuric acid.[5] In each process, the operating pressure is atmospheric.

Laboratory demonstrations have shown the manufacture of sulfuric acid benefits from higher operating pressures. Zeisberg [15] and Busching [1] have shown that both higher yields in sulfur dioxide conversion and effectively improved sulfur trioxide absorption are observed at elevated pressures.

Relatively few articles have been written describing the detail economics associated with a pressure sulfuric acid plant. Richterova [13] cites a reduction in both plant investment and operating costs using a gas expander. Cathala [4] suggests a minimum conversion pressure should be three atmospheres.

A comparison study is undertaken to define the economics, based on return on investment, for a pressure and conventional sulfuric acid plant.

DESIGN OF PROCESS

Introduction

Sulfuric acid manufacture involves three exothermic reactions.

$$S + O_2 \longrightarrow SO_2 \quad (3)$$

$$SO_2 + 1/2\ O_2 \longrightarrow SO_3 \quad (4)$$

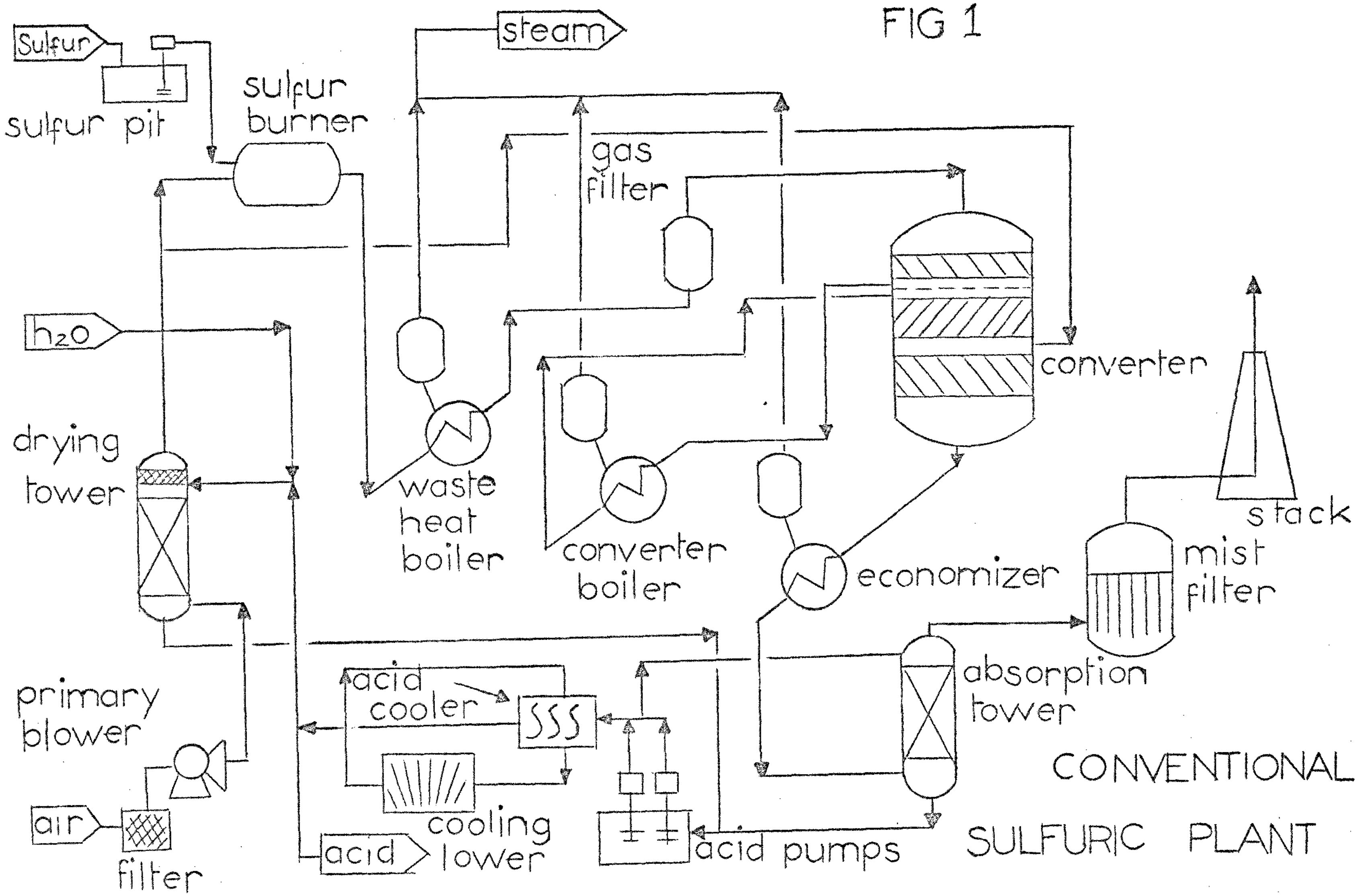
$$SO_3 + H_2O \longrightarrow H_2SO_4 \quad (5)$$

The conventional acid plant using the contact process and sulfur burning as the source of sulfur dioxide is schematically shown in Figure 1.

The burning of sulfur, described with equation (3), is accomplished in the presence of excess air which has been dried with concentrated acid. The reaction products leave the sulfur burner at the adiabatic flame temperature and are then cooled and filtered before entering the sulfur dioxide converter.

The oxidation of sulfur dioxide, reaction (4), is carried out in an adiabatic fixed bed catalytic reactor. The equilibrium characteristics and high degree of conversion required in sulfuric acid manufacture is

FIG 1



CONVENTIONAL SULFURIC PLANT

obtained in several stages or beds with cooling between stages. The reaction gases are cooled indirectly after the first bed and directly after subsequent beds.

Prior to entering the absorption column, the converter gases are cooled in a waste heat boiler.

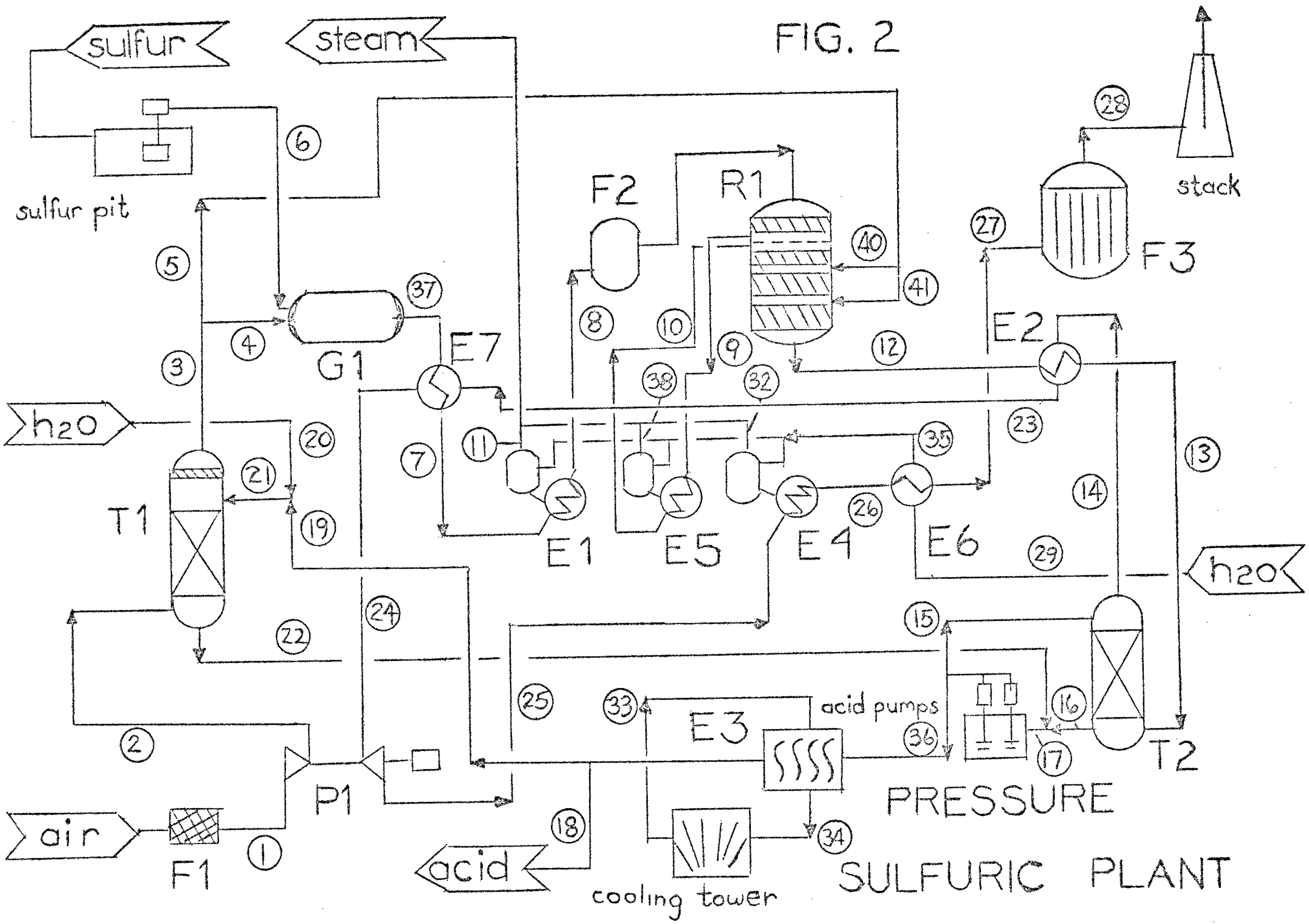
Energy released in cooling gases leaving the sulfur burner, and first and last bed of the converter is recovered as steam.

Finally, the absorption of sulfur trioxide in concentrated acid is accomplished in a ceramic ring packed tower. The gases leaving the absorption tower are essentially free of sulfur trioxide. The emission however, does contain unconverted sulfur dioxide and acid mist. Acid mist is removed in the mist filter and unconverted sulfur dioxide is released to the atmosphere.

The primary blower, usually operating at a discharge pressure less than five psig, delivers the process gases throughout the plant.

A proposed pressure plant, shown in Figure 2, closely resembles the conventional plant except an air

FIG. 2


sulfur
steam
sulfur pit
F2
R1
stack
F3
G1
E7
E1
E5
E4
E6
E2
T1
T2
h2o
h2o
air
F1
P1
acid
E3
acid pumps
cooling tower
PRESSURE
SULFURIC PLANT
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compressor-expander replaces the primary blower and heat exchangers are re-arranged to provide energy recovery. The heat exchanger arrangement generates steam and provides a high temperature gas feed to the expander required for operating cost economy. The equipment numbers, introduced in Figure 2, are defined in Tables III, IV and V.

For the purposes of this study the following operating conditions and rates are used to illustrate the effect of pressure on plant economics.

Rate = 1000 N.T. Sulfuric per Day

Converter Feed Concentration = 8 percent SO_2

Efficiency = 95 percent (based on sulfur)

Overall Conversion = 99 percent

Approach to Equilibrium = 95 percent of equil. conver.

The above conditions could be varied by modifications in the input data of the computer program.

Conditions that are considered fixed, based on operating guidelines for convertional plants, are listed in Table I. The stream numbers are identified in Figure 2.

TABLE I

OPERATING GUIDELINES FOR A

SULFURIC ACID PLANT

Stream Number	Assumptions [5]
(1)	Relative humidity equals 50 percent
(3)	Water content at 1 mg per cu. ft. and at a temperature 1 degree less than (21)
(6)	Temperature at 127 deg. F
(8)	Temperature at 450 deg. C
(11) & (32) & (38)	Saturated steam at 250 lbs. per sq. in.
(13)	Temperature at 450 deg. F
(14)	Temperature at 1 deg. > than (15)
(15) & (21)	Circulation rate at 2.5 gal per daily ton of acid, gravity at 15.2 lbs. per gal.
(10) & (40) & (41)	Converter feed temperature at 400 deg. C
(18)	Acid temperature at 100 deg. F and concentration at 98 percent
(16) & (22)	Heats of dilution based on graphical data D.&W. [5] p. 440
(24)	Temperature at 1000 deg. F
(26)	Temperature at 450 deg. F
(27)	Temperature at 250 deg. F
(37)	Adiabatic flame temperature at 890 deg. C based on 8 percent SO_2 from burner

I. Heat and Material Balance

The calculations for the heat and material balance follow the conventional mole balance starting with an overall material balance. Assumed thermal conditions are matched by successive iterations through the plant balance.

Enthalpy coefficients are derived for the process gases in the plant using the definition of heat capacity as a function of temperature.[14]

$$C^*_{pi} = \alpha_i + \beta_i T + \gamma_i T^2 \tag{6}$$

$$C^*_{p\,MIXTURE} = y_A C_{pA} + y_B C_{pB} + y_C C_{pC} + ---- \tag{7}$$

$$\Delta H_i = m_i * 1.8 \int_{T_o}^{T} C^*_{pi}\, dT = \sum_i m_i * COF_i \tag{8}$$

The total change in enthalpy resulting from heating and cooling gases is developed for plant components.

$$\Delta H = \sum_i \Delta H_i \equiv Btu \tag{9}$$

Using the reference temperature, T_o, equal to 298°K, the component coefficients are calculated.

$$COFN_2 : m_{N2} \left[11.743 * T + 1.125 * 10^{-3} * T^2 - 3599. \right] \tag{10}$$

$$COFO_2 : m_{O2} \left[11.066 * T + 2.792 * 10^{-3} * T^2 - 3546. \right] \tag{11}$$

$$COF\ SO2: \eta_{SO2}\left[12.809*T+8.561\times10^{-3}*T^{2}-4578.\right] \quad (12)$$

$$COF\ SO3: \eta_{SO3}\left[10.939*T+21.182\times10^{-3}*T^{2}-5141.\right] \quad (13)$$

Physical properties used in the balance are used from average operating conditions for the equipment. (See Appendix)

The logic and sequence of calculations are summarized in a computer block diagrams shown in Figure 3, 4 and 5.

II. Equipment Design

The design calculations for the various equipment in the pressure plant are located in Subprograms N89 and N90. Design equations and assumptions are described in this section.

(1) Converter design. The conversion of sulfur dioxide to sulfur trioxide is accomplished in a fixed bed catalytic reactor operating under adiabatic conditions. The high degree of conversion required in sulfuric acid manufacture is achieved by removing the large quantities of heat evolved by the heat of reaction.

The path of the reaction is illustrated in Figure 6.

Feed enters the converter, at point g, with essentially zero conversion and at a temperature greater than the ignition temperature of the catalyst. On contact

FIG 3
HEAT AND MATERIAL BALANCE
SUBPROGRAMS M88, N88
BLOCK DIAGRAM

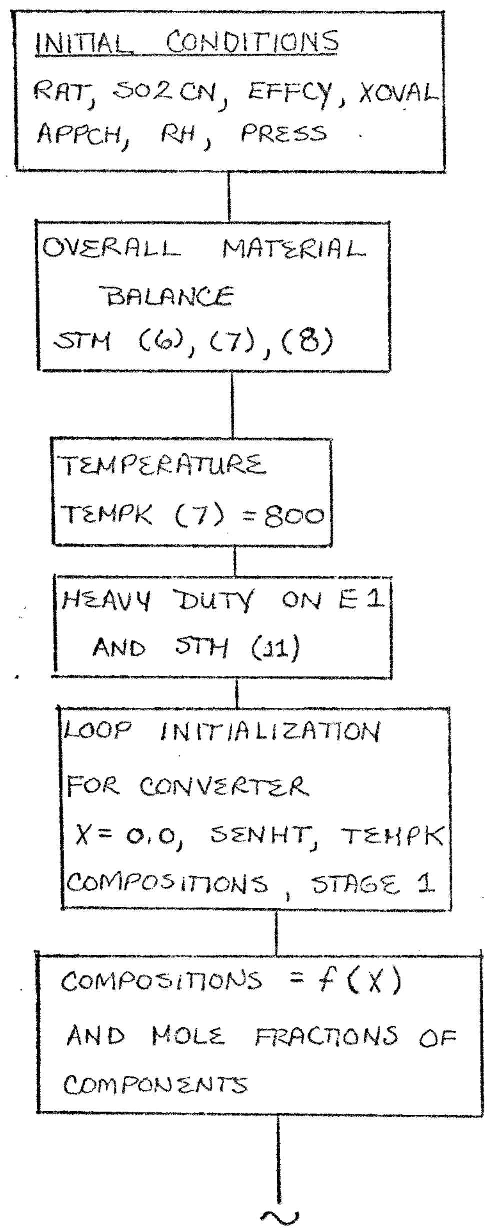


FIG4

HEAT AND MATERIAL BALANCE
M88 BLOCK DIAGRAM
(continued)

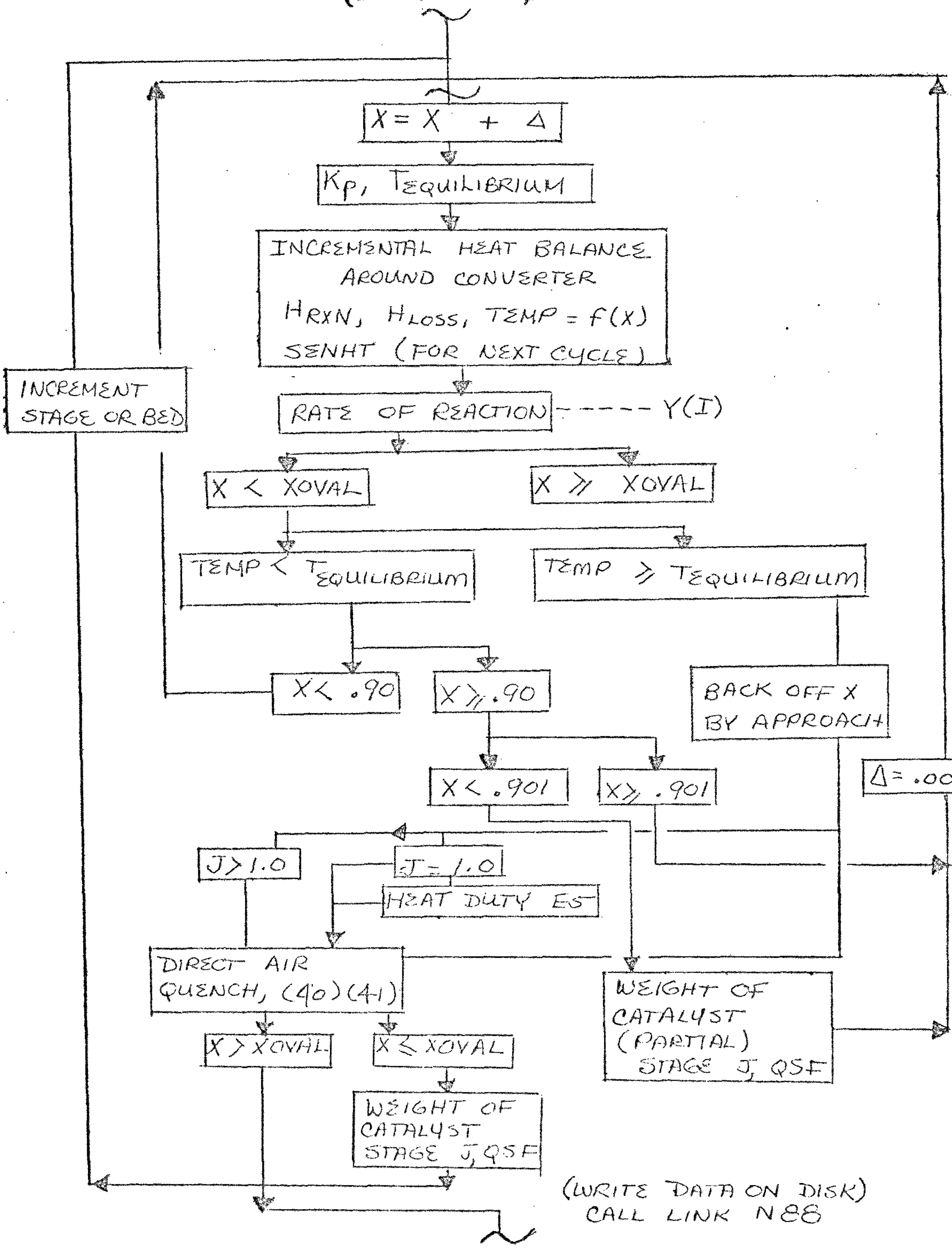


FIG 5

HEAT AND MATERIAL BALANCE

N88 BLOCK DIAGRAM

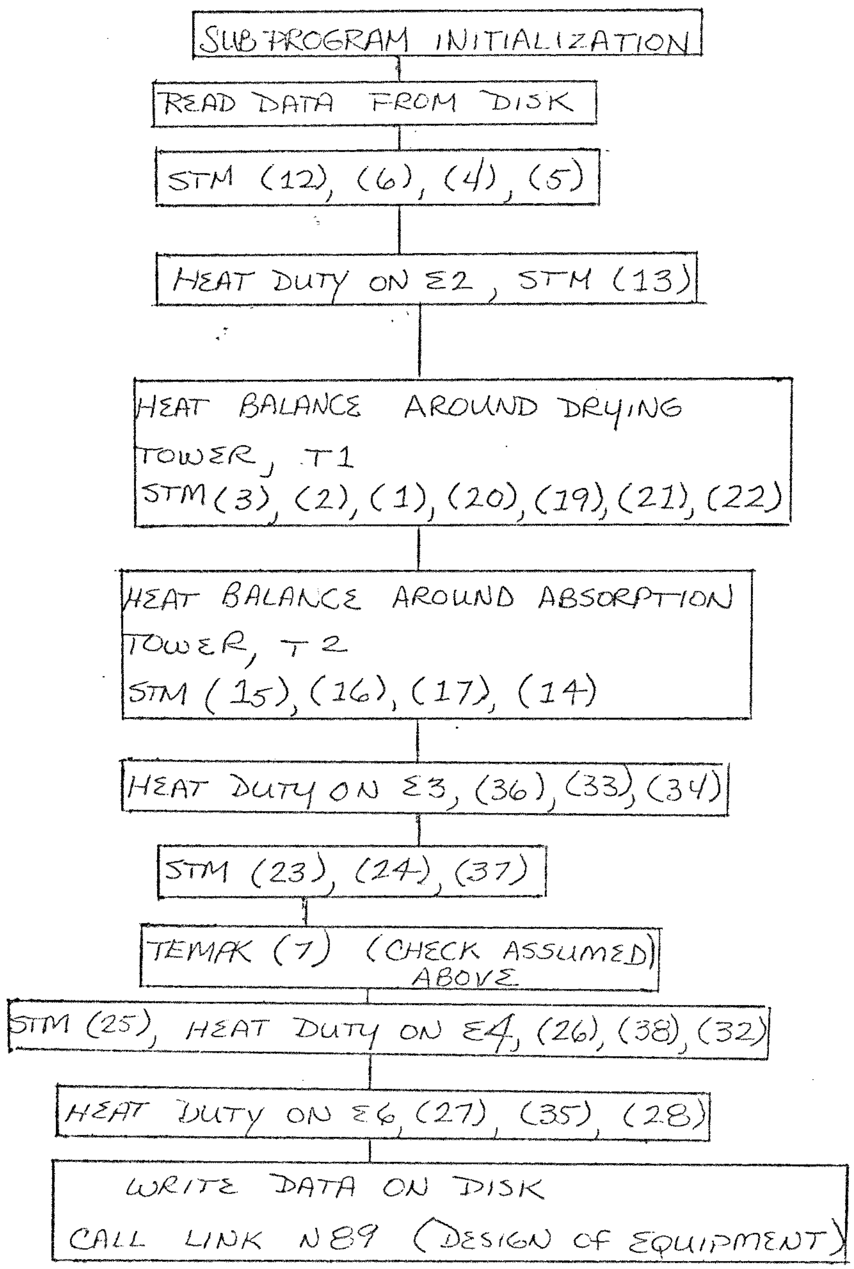
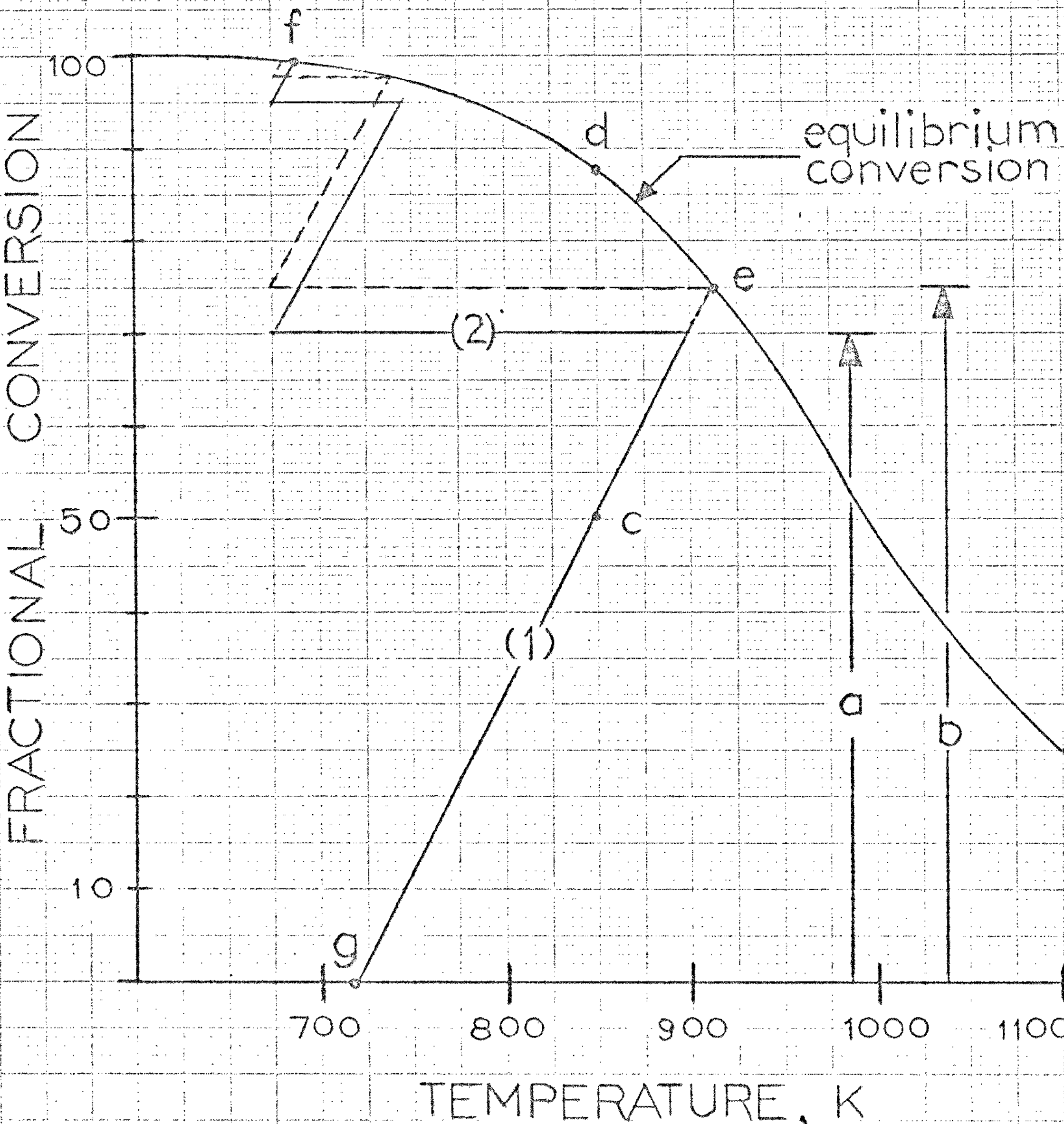


FIG. 6

CONVERSION
VS
TEMPERATURE



with vanadium pentoxide catalyst, the converter gas temperature increases along path (1) until the equilibrium conversion line is reached.

(a) Converter heat balance. An incremental heat balance equation is used to determine the resulting gas temperature for each unit conversion.[5]

$$\begin{pmatrix}\text{SENSIBLE HEAT}\\ \text{OF}\\ \text{REACTION PRODUCTS}\end{pmatrix} = \begin{pmatrix}\text{SENSIBLE HEAT}\\ \text{OF}\\ \text{REACTANTS}\end{pmatrix} - \left(\Delta H_{RXN} * X'\right) \quad (14)$$

Incorporating the enthalpy coefficients for the reaction gases developed in the previous heat and material balance section, the incremental heat balance is expressed as a second order linear equation.

$$COFA * T^2 + COFB * T + COFC = 0 \quad (15)$$

The coefficients of T squared in the gas enthalpy equation are expressed as a function of the moles of the various components.

$$\left[m_{N2} * 1.125 \times 10^{-3}\right] + \left[m_{O2} * 2.792 \times 10^{-3}\right] + \quad (16)$$

$$\left[m_{SO_2} * 8.561 \times 10^{-3}\right] + \left[m_{SO_3} * 21.182 \times 10^{-3}\right]$$

Likewise COFB is expressed in similar terms.

$$[m_{N2} * 11.743] + [m_{O2} * 11.066] + [m_{SO2} * 12.809] + [m_{SO3} * 10.939] \quad (17)$$

The remaining elements in the heat balance are collected in COFC.

$$COFC = -\begin{pmatrix}\text{SENSIBLE} \\ \text{HEAT} \\ \text{OF REACTANTS}\end{pmatrix} + (\Delta H_{RXN} * X') - H_{LOSS} + \text{CONSTANT} \quad (18)$$

The constant term collects residual terms in the gas enthalpy equation not covered with COFA or COFB.

$$\text{CONSTANT} = -3599 * m_{N2} - 3546 * m_{O2} - 4578 * m_{SO2} + 5141 * m_{SO3} \quad (19)$$

The resulting gas temperature for increments of conversion is obtained using the standard square root formula.

$$T = \frac{-COFB \pm (COFB^2 - 4\,COFA * COFC)^{1/2}}{2 * COFA} \quad (20)$$

The heat of reaction is expressed as a function of temperature using the heat capacity coefficients of the reaction gases.[5]

$$\Delta H_{RXN} = \Delta H^{\circ}_{RXN} + \Delta\alpha T + \frac{\Delta\beta}{2} T^2 + \frac{\Delta\gamma}{3} T^3 \quad (21)$$

where

$$\Delta H^{\circ}_{RXN} = -42{,}340 \ \frac{\text{Btu}}{\text{\# moles } SO_2} \ \text{AT } 298^{\circ}K$$

In the final form:

$$\Delta H_{RXN} = -41{,}631 - 4.113T + 6.236 \times 10^{-3} T^2 - 1.246 \times 10^{-6} T^3 \quad (22)$$

(b) Converter equilibrium calculation. The true equilibrium constant for the reversible reaction is a product of three terms.

$$K = K_\gamma * K_\phi * K_p \quad (23)$$

K_γ is difficult to calculate and usually is assumed equal to 1.0.[14] Gas mixtures produced in sulfuric acid manufacture behave as ideal gases. A deviation $< 2\%$ has been calculated at pressures of 200 psig. For ideal gas behavior K_ϕ equals 1.0. Therefore, for the reaction $SO_2 + 1/2\ O_2 \longrightarrow SO_3$:

$$K = K_p = K_y \pi^{C_{SO3} - C_{SO2} - C_{O2}} \quad (24)$$

$$K = K_p = \left(y_{SO3} / y_{SO2}\, y_{O2}^{1/2} \right) * \pi^{-1/2} \quad (25)$$

Using an empirical equation for the equilibrium constant K_p,[5]

$$\log_{10} K_p = 4956/T - 4.678 \equiv ATM^{-1/2} \quad (26)$$

A relation is obtained to calculate the equilibrium temperature for a gas mixture and absolute pressure.

$$T_{EQUILIBRIUM} = \frac{4956}{\log_{10} K_p + 4.678} \qquad (27)$$

Equation (27) is used to determine when the equilibrium conversion line has been reached, along path (1). A comparison is made between the reaction gas temperature, calculated by the incremental heat balance, and the equilibrium temperature. This comparison is illustrated in Figure 6 using points C and D. A comparison continues until the maximum conversion for the first converter bed is obtained at point E. No further conversion is possible until the reaction gases are cooled along path (2).

Alternate adiabatic heating by the reaction and cooling between beds continues until the desired final conversion is obtained (point F.).

The cooling of reaction gases is accomplished by direct injection of air after the second and subsequent stages.

(c) Converter catalyst requirement. The quantity of catalyst required to obtain a specified conversion is dependent on the rate of reaction as described in the following equation.[2]

$$\omega = F \int_{x_1}^{x_2} \frac{1}{r}\, dx \qquad (28)$$

At points close to the equilibrium conversion line, the weight of catalyst required becomes infinite due to the small concentration driving force. For the purposes of this study a practical approach to the equilibrium conversion point is set. Using the ordinate as a reference, the approach to equilibrium is fixed at 95 percent as illustrated in Figure 6.

$$\text{Approach to Equilibrium} = \frac{a}{b} = 95 \text{ percent} \qquad (29)$$

Design conversion is obtained by calculating the equilibrium conversion and backing off 5 percent to the design approach.

Several forms of the rate of reaction have been developed from experimental investigators. Calderbank's [2] equation for an operating pressure of 1 atmosphere is presented in equation (30)

$$r = (8.5\times10^6)\left\{\left(e^{-31,000/RT + 12.07} * \frac{P_{O2}P_{SO2}}{P_{SO2}^{1/2}}\right) + -\left(e^{-53,600/RT + 22.75} * \frac{P_{SO3}P_{O2}^{1/2}}{P_{SO2}^{1/2}}\right)\right\} \quad (30)$$

The total pressure contributes in the rate expression by using the definition of partial pressure of the gas in terms of mole fractions and total pressure.

$$P_i = y_i \, \pi \quad (31)$$

ie
$$\left(\frac{P_{O2}P_{SO2}}{P_{SO2}^{1/2}}\right) = \left(\frac{y_{O2}\,y_{SO2}}{y_{SO2}^{1/2}}\right)\pi^{1.5} \quad (32)$$

and
$$\left(\frac{P_{SO3}P_{O2}^{1/2}}{P_{SO2}^{1/2}}\right) = \left(\frac{y_{SO3}\,y_{O2}}{y_{SO2}^{1/2}}\right)\pi \quad (33)$$

A form of the rate expression which has been found to more closely characterize commercial converters is defined by Eklund.[5]

$$r = (8.5\times10^6)\; k^*\left(\frac{P_{SO2}}{P_{SO3}}\right)^{1/2}\left[P_{O2} - \left(\frac{P_{SO3}}{P_{SO2}K_{Eq}}\right)^2\right] \quad (33A)$$

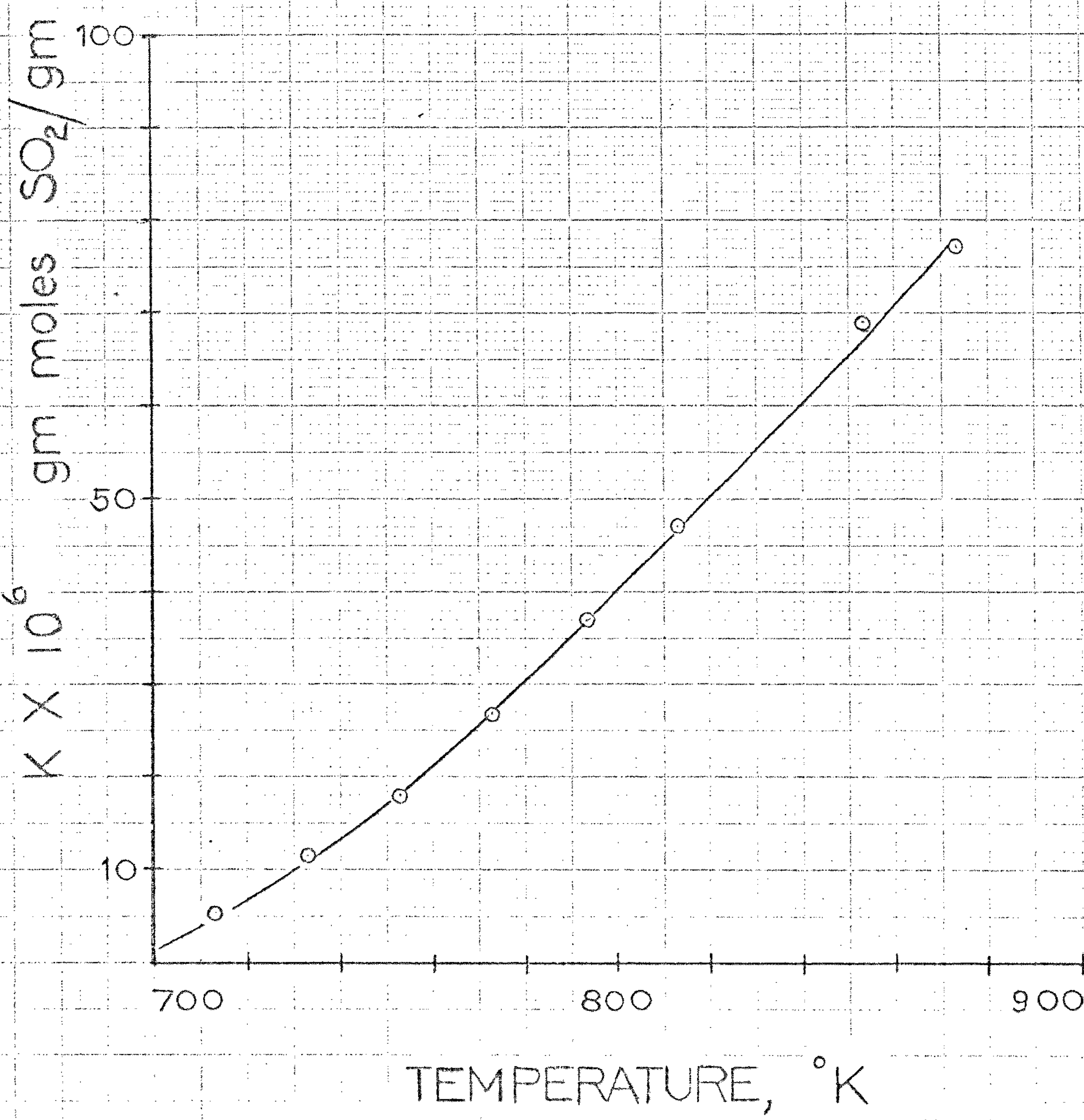
Eklund presents empirical data for k^*, the velocity constant, using 8 MM diameter by 25 MM catalyst. The data is graphically shown in Figure 7. The value of k^* can be expressed as a polynomial as a function of temperature. The results of a regression computer

FIG. 7

EKLUND DATA

K vs T

(catalyst 8 mm Ø x 25 mm)



program gives an expression with an average difference of 1.22 percent from empirical data.

$$k^* = \eta + \mu' T + \xi T^2 + m T^4 \tag{34}$$

where η = .004248

μ' = - .00001471

ξ = .1411 x 10^{-7}

m = - .3580 x 10^{-14}

The final Eklund rate equation, including the effect of total operating pressure, is expressed in equation (35).

$$r = 8.5 \times 10^6 * k^* \times \left(\frac{y_{SO2}}{y_{SO3}}\right)^{1/2} \times \left(\left(y_{O2}\pi - \frac{y_{SO3}}{y_{SO2} K_p}\right)^2\right) \tag{35}$$

Laboratory studies [2] show the rate determining step in the oxidation of SO_2 is the rate of oxidation of chemisorbed SO_2 by oxygen in the gas phase. These results indicate the velocity constant, k*, is dependent only on temperature and equation (35) should be valid at higher pressures.

The Scientific Subprogram, QSF, used to integrate quantities in equation 28, requires equal increments of conversion. On this basis, increments of conversion at 0.01 are used for conversion up to and including 90 percent. Further conversions are incremented by units equal to 0.001.

The size of the converter is established from the calculated catalyst per stage obtained in program M88. An additional 15 percent catalyst is added to each bed to compensate for gradual loss in catalyst activity with age.

A block diagram of the computer program used to calculate the quantity of catalyst and stages is shown in Figure 4.

(d) Converter diameter and height calculation. The diameter of the vessel is obtained on the basis of superficial gas velocity in the converter. Ideal gas behavior is used for the gas volume calculations. Using a design velocity of conventional plants at 100 cu. ft. per min. per square feet (S.C.), the allowable velocity is adjusted for pressure to maintain an approximate equivalent pressure drop per foot of catalyst. The allowable superficial velocity is found to be inversely proportional to the square root of the total pressure. The converter cross sectional area and diameter are obtained from the ratio of volumetric gas flow per unit time and allowable superficial velocity. The converter height is obtained from the total catalyst per stage, in pounds, and a catalyst density at 40 pounds per cu. ft.

$$\text{Height of Catalyst} = \text{Volume of Catalyst} \,/\, \text{Cross Sectional Area} \qquad (36)$$

An additional height of 15 percent times the diameter is allowed between stages for access and air sparge connections. Also an additional 15 percent is provided for the height of vessel above and below the first and last bed.

(e) Converter pressure drop calculation. The pressure drop across the converter is calculated from a correlation for flow through static beds.(11)

$$\Delta P = \frac{2 f_m G^2 L}{144 D_p g_c \rho} \qquad (37)$$

where $f_m = 79.5 / Re^{.375}$

and $Re = \dfrac{D_p G}{\mu}$

The computer program to calculate the converter design is shown in Figure 4.

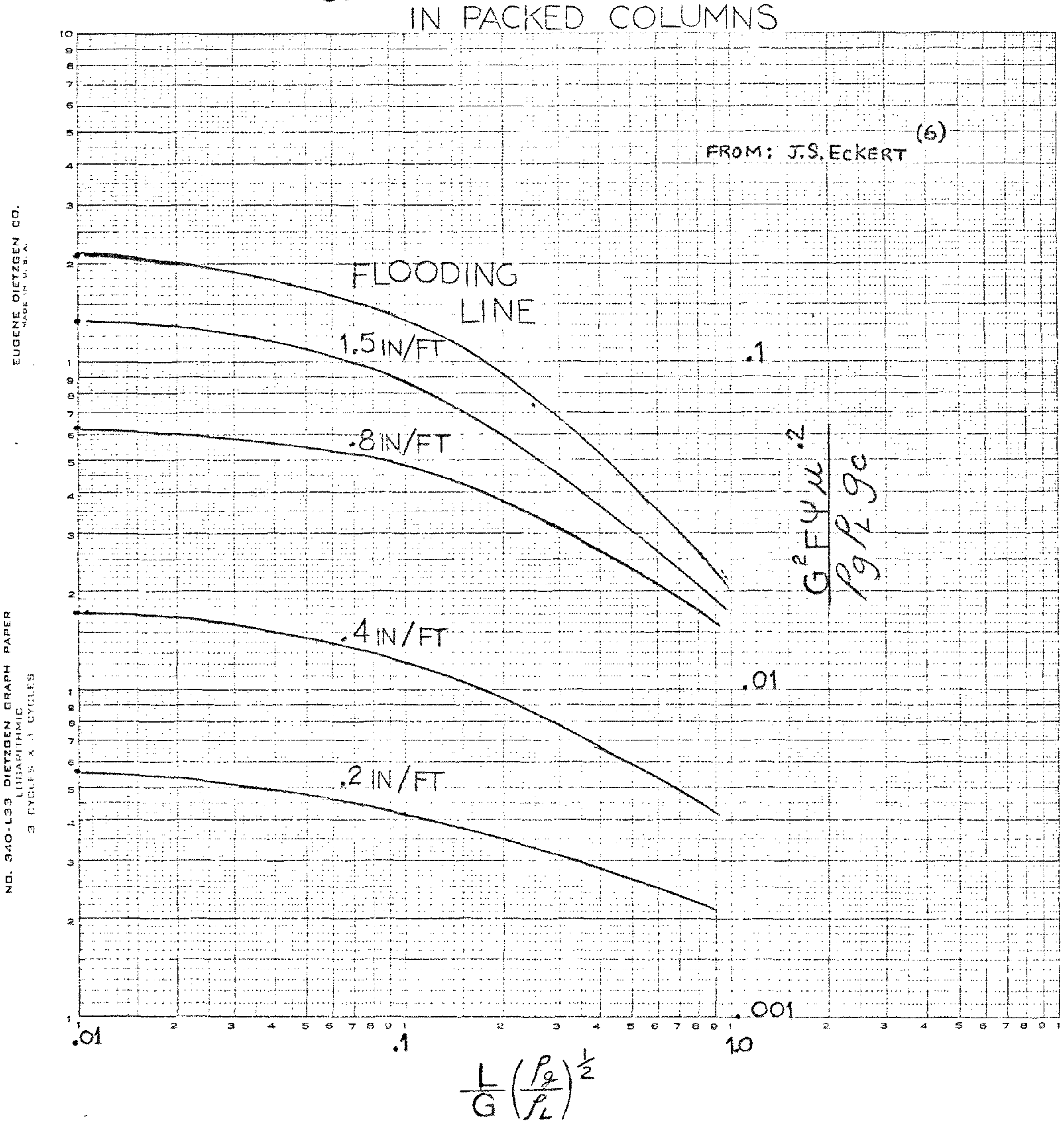
(2) Absorption and drying tower. The absorption of sulfur trioxide in concentrated sulfuric acid and the drying of air with concentrated acid requires intimate contact for both heat and mass transfer. Towers packed with ceramic raschig rings provide the surface necessary for both modes of transfer.

The relations used in a packed tower design are derived from empirical correlations developed by Eckert.[6] A generalized correlation is shown in Figure 8.[6]

The general curve establishes the maximum allowable gas velocity in a packed column as a function of gas and liquid flow rates, physical properties and packing characteristics.

The flooding line on Figure 8 identifies the point at which the gas velocity prevents the "regular" down flow of liquid. For Raschig Rings, flooding generally occurs at pressure drops equal to 1.5 inches of water per foot of packing. The normal design basis is to select a

FIG. 8
GENERALIZED PRESSURE DROP
IN PACKED COLUMNS



column diameter which gives an approximate 50 percent of the flooding point. (ie .75 inches of water per foot of packing) A 50% loading factor is used in the computer program.

(a) <u>Calculation of tower diameters</u>. A graphical procedure is not convenient for use on a computer. An arithmetical procedure has been developed by Prahl [12] based on the generalized curve. In this procedure, the design correlation is numerically characterized by four numbers, particular to the type of packing and packing size.

The arithmetical equations defined by Prahl to calculate the cross sectional area are listed below.

$$a = l/g \left(\rho_g / \rho_L \right)^{1/2} \tag{37}$$

$$m' = pa + q \tag{38}$$

$$n' = ra + s \tag{39}$$

$$o = \Delta p' / (m' \Delta p' + n') \tag{40}$$

$$A_x = g/\rho_L \left(\mu'^2 / \rho_g * o \right) \tag{41}$$

The specific parameters that characterize 2 inch Rasching Rings used in this study are listed.

$p = 3.77 \times 10^3$

$q = .754 \times 10^3$

$r = 2.09 \times 10^3$

$s = .880 \times 10^3$

$\Delta p' =$ .75 inch of H_2O per foot (based on superficial flooding velocity)

The design diameter of the tower is obtained from the cross sectional area. Volumetric gas flow are based on ideal gas behavior.

(b) Calculation of tower height. The absorption of SO_3 (g) involves the release of large quantities of energy.

$$SO_3\ (g) + H_2O\ (l) \longrightarrow H_2SO_4\ (\ell) \qquad (42)$$

$$\Delta H_{RXN} = 697\ \frac{\text{Btu}}{\#\ SO_3(g)}$$

It is assumed the surface required to transfer heat from the gas to the acid is the controlling factor in the packed tower design and controls over the area required for the corresponding mass transfer rate.

The "j" factor analysis [10] is used to calculate the heat transfer coefficient.

$$j = \frac{h}{C_p G_o} \left[\frac{C_p \mu}{k}\right]_f^{2/3} = 1.06 \left[\frac{D_p G_o}{\mu}\right]^{-.41} \tag{43}$$

The temperature driving force is calculated using a point to point analysis up the column. The surface area of packing required for heat transfer is calculated using:

$$\int_{T_o}^{T_1'} \frac{dT'}{T'-t} = \int_0^A \frac{h}{\omega C_p} = \frac{hA}{\omega C_p} \tag{44}$$

The relationship between the packing surface area and packed volume is used to calculate the height of packing. For 2" raschig rings

$$\text{Height of Packing} = \frac{\text{Area (heat transfer)}}{28 \frac{\text{sq.ft.}}{\text{cu. ft.}} \times A_x} \tag{45}$$

For operating conditions which are not controlled by heat transfer cosiderations, the geometric relationships of conventional plants are maintained.

The total column height is made up of the packing sections, and an additional 30 percent of the column diameter to allow for top and bottom sections of the column and regions required liquid distribution mechanisms.

No single bed height is allowed to exceed three times the diameter.

Physical properties used in design are based on average operating conditions in the towers. (See Appendix)

(3) Heat exchange design. Heat transfer equipment is essential in maintaining energy economy in a sulfuric acid plant. A very important by product of acid manufacture is the energy released from heat of reaction in the gas burner and converter and heats of formation in the absorber and drying tower. The design arrangement selected for the pressure plant involves several types of heat transfer design conditions.

(a) Gas/Gas Transfer

(b) Gas/Steam Transfer

(c) Gas/Liquid Transfer

(d) Liquid/Liquid Transfer

(a) Design of gas/gas heat exchangers. The transfer of heat from one gas stream to another gas stream requires the greatest capital investment due to the low heat transfer coefficients. The basis for this equipment design is selected from McAdams,[10] using the section covering optimum operating conditions for shell and tube exchangers.

The following assumptions are used in the heat exchanger calculations.

a) Physical properties are estimated from average operating conditions. (See Appendix)

b) Annual fixed charges estimated at 20 percent of installed cost.

c) Operating factor is 95 percent or 8300 hrs. per year.

d) Power cost to the fluid equals $.02 per kw - hr. for both shell and tubes.

e) Exchanger tubes @ nominal 2 inch diameter and square pitch @ 1.5 Do

f) Turbulent flow in tubes and shell.

g) Safety factor is 1.25 or 25 percent over design from theoretical.

h) Shell side is unbaffled.

i) Length of tubes equal 20 feet

(a1) Calculation of optimum velocities. The optimum mass velocities for both the shell and tubes are obtained from the physical properties of the process streams and mechanical features of the heat exchanger. The basic design equations used include the following dimensionless terms,

$$* \quad B_i = \frac{1 + N_{TP} \, K_1 \, (a_3/a_i)}{\phi_i \, F_s} \tag{46}$$

$$* \quad B_i = 1.0 \qquad \text{(unbaffled exchanger)} \tag{47}$$

where
$$\phi_i = \frac{(t_2 - t_1)_i}{\Delta t_i} \left[\frac{c_p \mu}{k}\right]_i^{2/3} \tag{48}$$

and dimensional terms:

$$K_i = \frac{B_i \, a_i \, \mu_i^{m_i'}}{2 g_c \, \rho_i^2 \, D_i^{m_i'}} \tag{49}$$

* Subscript i, o refer to conditions in tubes or in shell respectively.

$$K_o = \frac{2 B_o \, a_o \, y_o \, \mu_o^{m_o}}{\pi \, g_c \, \rho_o^2 \, D_i \, D_o^{m_o}} \tag{50}$$

The optimum mass velocities for the tubes and shell, G_{io} and G_{oo} respectively are calculated from unit cost C_{Ai}, C_{ei} and C_{eo}.

$$G_{io} = \left[\frac{(C_{Ai}/C_{Ei}) \, K_i}{2.5 + 2.76 \left(\frac{\Delta t_o}{\Delta t_i}\right)}\right] \tag{51}$$

$$G_{oo} = \left[\frac{(C_{Ai}/C_{Go})\ K_o}{3.75 + 3.39\ (\Delta t_i/\Delta t_o)} \right]^{.351} \qquad (52)$$

(a2) Calculation of heat transfer coefficients. The knowledge of mass velocities is used to calculate individual heat transfer coefficients.

$$(h/C_pG_o)_i \left(\frac{C_p\mu}{k}\right)_i^{2/3} = \frac{a_3/F_S}{(DG/\mu)_i^{1-n_i}} \qquad (53)$$

$$(h/C_pG_o)_o \left(\frac{C_p\mu}{K}\right)_o^{2/3} = \frac{a_4/F_S}{(DG/\mu)_o^{1-n_o}} \qquad (54)$$

(a3) Calculation of heat transfer area. The design procedures used on heat exchangers involves assuming an overall heat transfer coefficient, U, and calculating a trial surface area.

$$A = Q/(u \cdot \Delta T_{em}) \qquad (55)$$

The surface area is used to determine the hourly fixed charges on equipment, C_{Ai}, which is a function of area.

Individual film temperature drops Δt_i and Δt_o are assumed for the shell and tube side of the exchanger.

The assumed thermal resistances are checked from the mass velocities and individual heat transfer coefficients.

$$\frac{\Delta t_i}{\Delta t_o} = \frac{h_o}{h_i}\,\frac{D_o}{D_i} = 1.14\,\frac{h_o}{h_i} \qquad (56)$$

Using the correct thermal resistances, the assumed surface area is compared with calculated area, from individual heat coefficients.

$$U = \frac{1}{h_i} + .876/h_o \qquad (57)$$

(a4) Calculation of heat exchanger pressure drop. Pressure drops in the heat exchanger [10] are calculated from physical conditions.

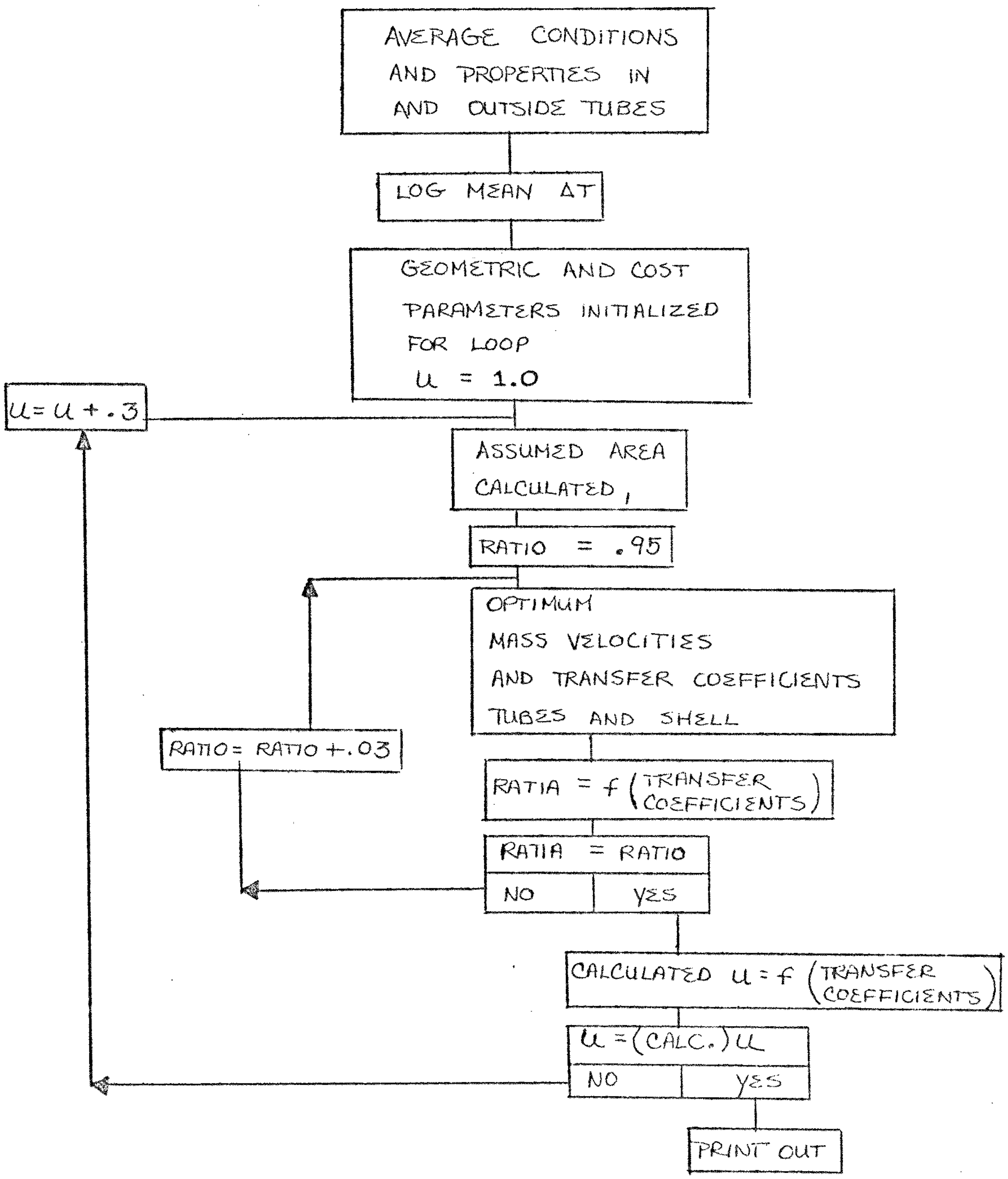
$$\Delta P_i = \frac{B_i\,4 f_i\,L_H\,G_{io}^2}{2 g_c\,\rho_i\,D_i} \qquad (58)$$

where $f_i = a_i\,(\mu/DG)_i^{m_i}$

and $$\Delta P_o = \frac{4 f_o\,B_o\,N\,G_{io}^2}{2 g_c\,\rho_o} \qquad (59)$$

The block diagram shown in Figure 9 illustrates the computer logic involved in heat exchanger design.

FIG 9
HEAT EXCHANGER
BLOCK DIAGRAM



b. <u>Design of gas/liquid heat exchangers</u>. Waste heat boilers involve heat transfer from the gas stream to water by generating steam.

The design equations used are again from McAdams[10] for the situation in which the shell side power is immaterial. The design equations, assumption, logic are essentially identical to the gas/gas design outlined above. For turbulent flow and low shell power costs the following equation is used.

$$G_{io} = \left[\frac{C_{Ai} \; C_{Ei} \; K_i}{3.5 \; \frac{\Delta t_m}{\Delta t_i} - 1} \right]^{.357} \qquad (60)$$

The design equations for the transfer of heat from a gas to a liquid involves the same design equation for optimum velocity on the tube side described above, however a heat transfer coefficient on the shell side is assumed. An individual shell side coefficient of 150 Btu/(Hr) (Sq. ft.) (deg F) is used.[10]

(c) <u>Design of liquid/liquid heat exchangers</u>. The liquid to liquid heat transfer for acid coolers is not contained in the computer design program since it is not strictly dependent on pressure. For this exchanger an overall coefficient equal to 100 Btu/(Hr) (Sq ft) (^{o}F) is used.[10]

(4) Compressor / expander. A compressor and gas expander combination has been accepted as an effective device to maintain thermal economy in systems with exothermic reactions and favoring higher operating pressures. The modern nitric acid and ammonia plants are examples of this arrangement.

The characteristics of sulfuric acid manufacture are very similar to both nitric acid and ammonia, however, the stoichiometry is less favorable. It would appear a compressor - expander combination could also contribute in making a pressure sulfuric acid plant more attractive by reducing investment and operating costs. To date, no commercial pressure plants are in operation.[5]

The compression of large volumes of air used in the oxidation of sulfur requires considerable power. The conventional sulfuric acid plant is designed to give a minimum pressure drop across process equipment and thereby reducing total power consumption. A typical power requirement for a conventional plant, rated at

1000 NT per day Sulfuric Acid and 40 inch water S.P., is 700 H.P. This primary blower is usually turbine driven.

The power needed for a pressure sulfuric acid plant is much higher than the conventional plant. To justify the pressure operation, an energy recovery system is a necessity.

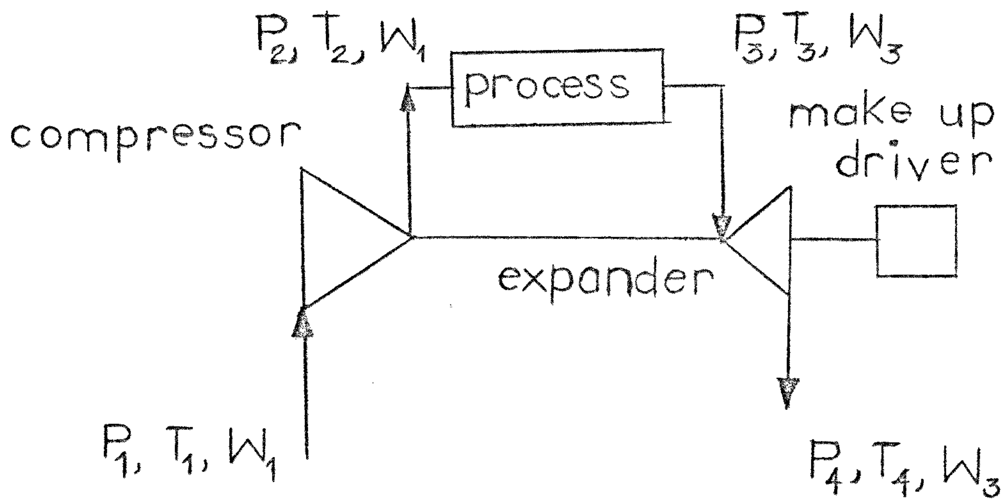
A compressor - expander shown in Figure 10, illustrates a typical scheme for power recovery. Air, at atmospheric pressure, is compressed in a centrifugal compressor and used to advantage in the process. Gases are released to a gas expander at a slightly reduced absolute pressure due to pressure loss across the plant. The exothermic reactions allow for maximum utilization of power recovery through the expander.

The compressor and expander are linked together through a common shaft. Additional power, not recovered by the expander, is supplied by an electric motor.

The basic relations for power recovery have been developed by Canova.[3] For uncooled compression the

FIG 10

COMPRESSOR / EXPANDER SYSTEM



make up horsepower, E, [3] is calculated from operating conditions and physical properties.

$$\frac{E}{\sqrt{\theta_1}\,\xi_1} = \left(50.3 * \frac{\omega_1\sqrt{\theta_1}}{\xi_1}\right) * \left[\frac{\left(P_2/P_1\right)^{\frac{k'-1}{k'}} - 1 - C\left(1 - \frac{P_3 P_2}{P_2 P_1}\right)^{-\left(\frac{k'-1}{k'}\right)}}{\eta_c (k'-1)/k'}\right] \qquad (61)$$

The compressor - expander will sustain itself if the temperature to the expander is sufficiently high. The basic relation for the self-sustaining temperature is given by the following equation.[3]

$$\frac{T_3}{T_1} \quad \frac{R_1/R_3\left[\left(P_2/P_1\right)^{-(k'-1)/k'} - 1\right]}{\left(\omega_3/\omega_1\right)\eta_c\,\eta_e\left[1 - \left(P_3 P_2/P_2 P_1\right)^{-(k'-1)/k'}\right]} \qquad (62)$$

The assumptions (3, 13) used to calculate power usage for the expander arrangement are listed.

k' = 1.401

η_c = .65

η_e = .85

P_3/P_1 = .90

$T_3(MAX)$ = $1000^\circ F$

$(P_2/P_1)_{MAX}$ = 13

ω_1 = based on 1000 NT acid/day

The sizing of the centrifugal compressor, for cost purposes, is obtained from a series of charts and graphs presented by Hallock.[8]

(5) Miscellaneous equipment. Four pieces of equipment are not dependent on pressure due to gas volume. These items include: 1) Acid Cooler, E3, 2) Sulfur Pit 3) Acid Pumps and 4) Cooling Tower.

The acid cooler is designed from heat and material balance considerations using an overall heat transfer coefficient equal to 100 Btu/Hr/Ft $^2/^oF$. [10]

The Sulfur Pit is designed from conventional arrangements outlined in Duecker & West[5].

Acid pumps are designed from material balance considerations.

The cooling tower is designed from the heat balances and a range of cooling equal to 20 degrees F on the recirculated cooling water.

BASIS FOR ECONOMIC CONSIDERATIONS

Return on Investment is used as a measure of the economic worth of a project by incorporating capital investment, operating cost, and burdens. Rate of return can also serve as a basis for comparing and selecting the most attractive operating condition for a pressure sulfuric acid plant.

Cost data, developed for a conventional sulfuric acid plant,[9] are adjusted to reflect economic differences resulting from operating pressure.

The fixed capital investment is obtained from estimating factors developed to calculate installed cost, on a preliminary basis.

Operating costs and burdens are assumed equivalent for equal capacity plants, however, power costs are adjusted to incorporate the use of the compressor expander.

Equations used to compare the effect of operating pressure include rate of return on investment and payout period.

$$\text{Return on Investment (\%)} = \frac{\text{Profit after Taxes}}{\text{Fixed Capital} + \text{Working Capital}} \qquad (1)$$

$$\text{Payout (years)} = \frac{\text{Fixed Capital}}{\text{Profit after Taxes} + \text{Depreciation}} \qquad (2)$$

DETERMINATION OF TOTAL COST

A module technique used to make preliminary capital cost estimates is presented by Guthrie [7]. The method consists of applying multipliers on the F.O.B. equipment cost to estimate the various components that make up the total installed cost. A variety of specific chemical plant equipment is correlated and allows a comparative analysis of the effect of pressure on capital investment.

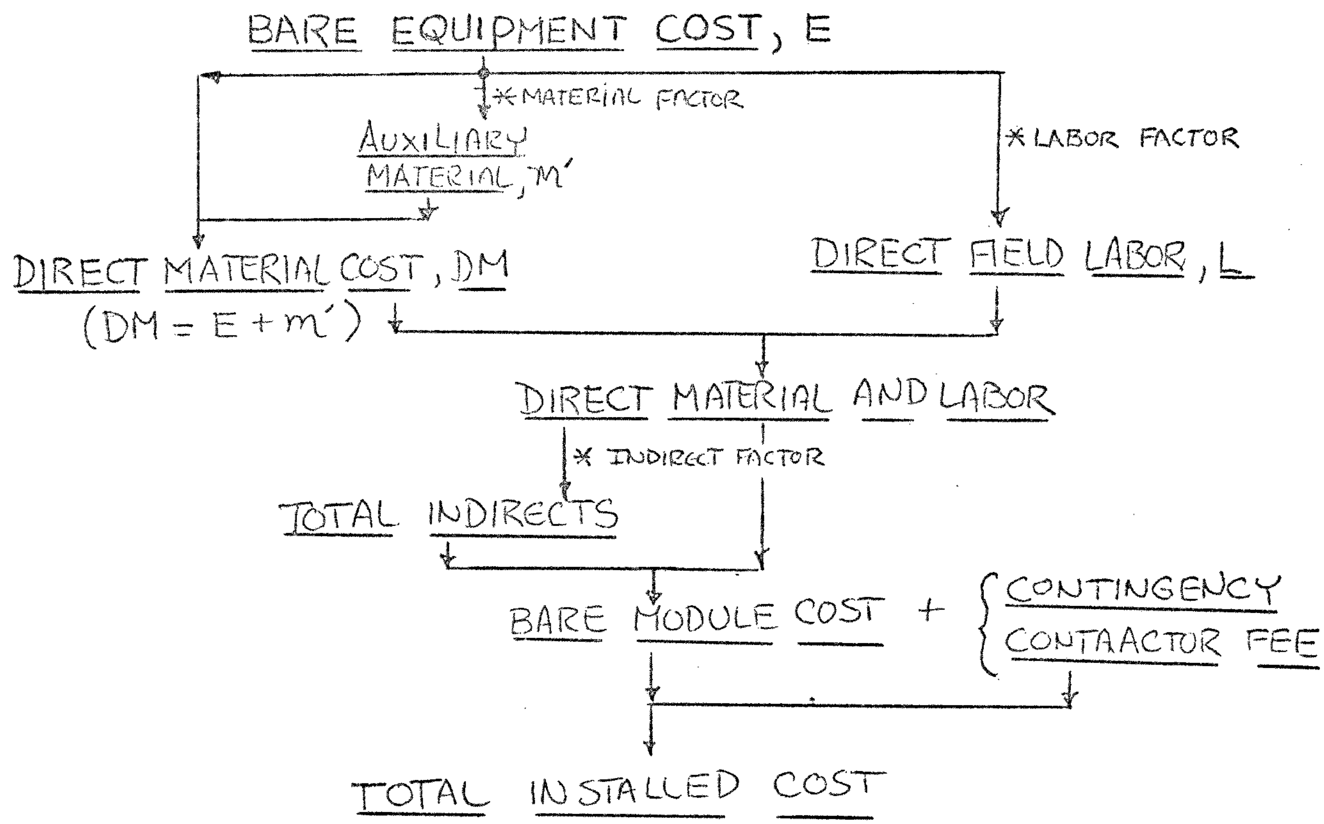
An schematic outline of factors that make up the total installed cost is shown in Figure 11.

The material factor, M.F., is the multiplier applied on F.O.B. cost which gives the total direct material cost including auxiliary material, such as piping, concrete, equipment steel, instruments, electrical, insulation and paint.

A labor factor, LF, when applied on the F.O.B. cost gives the cost of material erection and equipment setting.

Indirect costs are also obtained by applying a multiplier on F.O.B. cost. Indirects include elements of cost which are a percentage of direct material cost

FIG. 11
TOTAL INSTALLED COST BY MODULE ANALYSIS



such as sales, taxes, freight, insurance and duties. Also included in the indirect cost are items which are a percentage of direct field labor. Fringe benefits, labor burdens, supervision, temporary facilities, construction equipment, and construction overhead make up this category. Finally, the cost for project engineering process engineering, design and drafting, procurement, office overhead and contractor engineering cost, all of which being a percentage of direct material cost, make up the balance of indirect cost.

The sum of direct material and labor and indirect cost is defined as the bare module cost.

The addition of contingency and contractor's fees to the bare module cost gives the total installed cost. A 20 percent adjustment to the bare module cost is used to cover the contractor's fee and contingency.

The F.O.B. cost, based on mid-1968 and c - steel construction, is presented by Guthrie [7] in graphical form related to equipment size. The base cost is adjusted for materials of construction, pressure rating, and design arrangement.

The following equations are used to adjust the Base Equipment Cost.[7]

EXCHANGER COST, \$ = (BASE COST $(F_d + F_p)$ * F_M) * INDEX (63)

PROCESS VESSEL COST, \$ = (BASE COST * F_M * F_p) * INDEX (64)

CENTRIFUGAL PUMP COST, \$ = (BASE COST * F_M) * INDEX (65)

COMPRESSOR COST, \$ = (BASE COST * F_d) * INDEX (66)

The factors that make up the total installed cost for various equipment are presented in Table II from Guthrie.[7]

The components and their design characteristics for the pressure plant are summarized in Tables III, IV, and V.

TABLE II

FIELD MODULE COSTS (7)

	SHELL AND TUBE HEAT EXCHANGER	VERTICAL TANK FABRICATION	HORIZONTAL TANK FABRICATION	CENTRIFUGAL PUMPS	COMPRESSOR
EQUIPMENT COST, F.O.B., E	100.0	100.0	100.0	100.0	100.0
PIPING	45.6	60.0	41.1	30.2	20.6
CONCRETE	5.1	10.0	6.2	4.0	12.3
STEEL	3.1	8.0	--	--	--
INSTRUMENTATION	10.2	11.5	6.2	3.0	8.2
ELECTRICAL	2.0	5.0	5.2	31.0	15.4
INSULATION	4.9	8.0	5.2	2.5	2.6
PAINT	0.6	1.3	.5	.8	.5
MATERIAL FACTOR, m	71.4	103.8	64.5	71.5	59.6
DIRECT MATERIAL AND LABOR	171.4	203.8	164.5	171.5	159.6
MATERIAL ERECTION	55.4	84.	52.2	60.0	49.8
AND EQUIP. SETTING	7.6	15.2	9.3	9.7	11.6
DIRECT FIELD LABOR, L	63.0	99.2	61.5	69.7	61.4
DIRECT MATERIAL AND LABOR	234.4	303.	226.0	241.2	221.0
FREIGHT, INSURANCE, TAXES	8.0	8.0	8.0	8.0	8.0
INDIRECTS	86.7	112.0	83.6	89.2	81.8
BARE MODULE FACTOR	329.1	423.0	317.6	338.4	310.8

TABLE III

EQUIPMENT DESIGN

EQUIPMENT	ARRANGEMENT	MATERIALS OF CONSTRUCTION	FM (RANGE)	Fp (RANGE)	NOTES(5)
TOWERS T1, T2	VERT. TANK, PACKING & SUPPORTS INTERN. ACID DISTRIBUTERS	C.S. SHELL; 4" TK. ACID BRICK (LINED); C.I. INTERNALS	1.0	1.0/1.15	PACKING - 2" RASCHING RINGS @$3.5/CU.FT.; ACID BRICK @ $5.50/SQ. FT. (1968 PRICES M.&LABOR)
SULFUR BURNER, G1	HORIZ. TANK WITH BURNER NOZZLE	C.S. SHELL; 4" TK. REFRACT. & 9" TK. FIRE-BRICK	1.0	1.0/1.15	4" REFRACT. @ $10.52 PER SQ. FT; 9" FIREBRICK AT $10.79 PER SQ. FT. TOTAL $21.31/SQ. FT.
HOT GAS FILTER, F2	VERT. TANK FILLED WITH FINELY CRUSHED FIREBRICK	C.S. SHELL	1.0	1.0/1.15	CRUSHED REFRACT. AT $3.0/CU. FT.
WASTE HEAT BOILERS, E1, E4, E5	BOILER: WATER TUBE TYPE (SPECIAL S./T. EXCHANGER)	C.S. S./T. REFRACT. LINED HEADS	1.2/ 2.0	0.0/.05	DESIGN FACTOR, Fd = 1.20 * TUBES ALONIZED
MIST ELIMINATOR F3	VERT. TANK WITH SPECIAL TUBE FIL-TERS	C.S. SHELL ACID BRICK LINED INTERN. 304 S.S.	1.15	1.0/1.15	MIST FILTERS AT $2000/ELEM. EACH ELEM. @ 1500 ACFM

TABLE IV

EQUIPMENT DESIGN

EQUIPMENT	ARRANGEMENT	MATERIALS OF CONSTRUCTION	FM (RANGE)	Fp (RANGE)	NOTES [5]
CONVERTER R1	VERT. TANK WITH CATALYST AND SUPPORTS	C.S. SHELL EXCEPT TOP SECTION ALONIZED.	1.07	1.0/1.15	VANADIUM PENTOXIDE CATALYST @ $1400 PER TON OR $1.30/LITER
RECUP. EXCHANGERS, E2 and E7	FIXED TUBE, S./T. EXCHANGER	C.S. SHELL AND ALONIZED TUBES	1.2/2.0	0.0/.05	DESIGN FACTOR, Fd EQUALS .8
ACID COOLER E3	FIXED TUBE, S./T. EXCHANGER	C.S. SHELL KARBATE TUBES	-	-	U[10] = 100 BTU/HR. FT^2 ^oF COST = $6 PER SQ. FT.
CONDENSATE HEATER, E6	FIXED TUBE, S./T. EXCHANGER	C.S. SHELL AND TUBES	1.0	1.0/1.15	DESIGN FACTOR, Fd EQUALS .8

TABLE V

EQUIPMENT DESIGN

EQUIPMENT	ARRANGEMENT	MATERIALS OF CONSTRUCTION	FM	Fp	NOTES
AIR COMPRESSOR, P1	MULTIPLE STAGE CENTRIFUGAL WITH EXPANDER	C - STEEL	-	-	DESIGN AND COST HALLOCK (8) TEMP. IN 67°F Cp/Cv = 1.401 UNCOOLED COMPRESSION Fd = 1.15 (GUTHRIE (7))
SULFUR PIT	SUBMERGED CONCRETE PIT WITH PUMP AND HEAT PLATES	CONCRETE AND CAST IRON	-	-	DESIGN BASED ON DEUCKER AND WEST (5)
ACID PUMPS	CENTRIFUGAL PUMPS	CAST IRON	1.0	1.0	DESIGNED AT 5500 gpm AND 100 psig
COOLING TOWER	COOLING TOWER, CONCRETE BASIN, PUMPS, DRIVES	-	-	-	CAPACITY EQUALS 10,000 GPM AT COOLING RANGE = 20°F GUTHRIE (7)

ECONOMIC COMPARISONS

Operating pressure is reflected in the investment and income factors for a one thousand ton per day plant to obtain a comparison of earnings at pressures equal to one, three, five, seven, nine and thirteen atmospheres.

A summary of the material unit prices and various components that make up the total manufacturing cost is presented in Table VI for a Conventional Sulfuric Acid Plant as presented by Krnonseder.[9] The total manufacturing cost is adjusted for operating pressure using Krnonseder's values as a base.

A summary of typical earnings is presented for the conventional plant [9] in Table VII. Operating pressure effect both capital investment and manufacturing cost in this tabulation. Working capital, sales income, and other expenses are assumed equal for equivalent capacity plants.

TABLE VI

TOTAL MANUFACTURING COST

CONVENTIONAL H_2SO_4 PLANT

(1000 NT/DAY)

		DOLLARS/TON ACID
I	RAW MATERIALS @ $40.00/TON SULFUR	13.48
II	UTILITIES AND BY PRODUCT CREDIT	
	STEAM CREDIT @ $ .50/M lbs	(1.10)
	WATER @ $ .02/M gal	.14
	POWER @ $ .01/KWH	.53
	FUEL @ $ .05/M gal	.16
		(.27)
III	OPERATING LABOR AND SUPERVISION	.23
IV	CAPITAL CHARGES, TAXES AND INSURANCE	.39
V.	MAINTENANCE, REPAIRS, ETC.	.46
VI	OVERHEADS	.91
	TOTAL	15.20

TABLE VII

EARNINGS FOR CONVENTIONAL

H_2SO_4 PLANT - 1000 NT/DAY

I.	INVESTMENT		
	FIXED CAPITAL		2,990,000
	WORKING CAPITAL		
	ACCOUNT RECEIVABLE	106,000	
	CASH	460,000	
	IN PROCESS INVENTORY	94,000	
	RAW MATERIAL INVENT.	409,000	
	FINISH PRODUCT INVENT.	106,000	
			1,175,000
A)	TOTAL INVESTMENT		4,075,000
II.	INCOME		
B)	SALES 330,000 TPY @ $ 18.03/Ton		5,954,000
	LESS MANUFACTURING COST @ $ 15.20/Ton		5,016,000
C)	GROSS INCOME		938,000
	LESS SALE EXPENSE		
	RESEARCH EXPENSE		
	ADMINISTRATION EXPENSE		
	ALL OTHER EXPENSE		500,000
	PROFIT BEFORE TAXES		438,000
D)	PROFIT AFTER TAX @ 50%		219,000

RESULTS OF STUDY

The results of the computer study are presented in a series of five tables and one graph.

Table VIII outlines the effect of pressure on equipment design for components which are pressure dependent.

Table IX illustrates how effectively the gas expander reduces operating costs compared to a motor driven compressor by the lower power requirement. The Table also lists the operating costs for various pressures of a compressor expander.

Table X summaries equipment cost as a function of operating pressure. All major pieces of equipment, except the compressor expander P1, are reduced in cost. A significant reduction in catalyst requirements is obtained at elevated pressures.

Table XI is used to compare capital investment of the conventional sulfuric acid plant with the proposed scheme developed for a pressure plant. For this design study, the additional fixed capital cost required at one atmosphere is due to the added recuperative heat exchangers needed in the pressure plant arrangement.

The economics evaluation of a pressure plant is summarized in Table XII. Since the scheme presented for one atmosphere is unattractive, the listing at pressure equals one is for the conventional sulfuric acid plant adjusted for the cost index operating basis.[9] The Table shows that a maximum return on investment occurs at a pressure of about 3 atmospheres. The return on investment, the basis objective function for this study, is shown graphically in Figure 12 as a function of pressure. These results are in agreement with experimental investigations by Cathala [4] and recent studies by Richterova [13] applying the modern gas expander in sulfuric acid manufacturing plants.

TABLE VIII

EQUIPMENT DESIGN

Equipment	Pressure, ATM (1)	(3)	(5)	(7)	(9)	(13)
F1 (Thousand ACFM)	79	26	14	10	7	5
*T1 (Diam. x Height)	16.5/21.5	13.1/17	11.4/14.8	10.7/13.9	10.2/13.3	9.6/12.5
G1 (Diam. x Height)	22.2/33.4	15.4/23.1	13. /19.5	11.6/17.4	10.7/16.	9.4/14.2
E1 (Sq. Ft.)	7,000	3,650	2,670	2,170	1,920	1,920
F2 (Diam. x Height)	10.8/10.8	6.4/6.4	5. /5.	4.3/4.3	3.8/3.8	3.2/3.2
R1 (Diam. x Height)	29.2/52.8	22.1/31.3	19.5/22.6	17.9/19.7	16.8/17.9	15.3/15.4
E5 (Sq. Ft.)	1,810	710	2,970	2,450	2,250	2,280
E2 (Sq. Ft.)	41,480	19,400	11,860	9,540	8,210	6,730
T2 (Diam. x Height)	18. /23.	14. /18.	12. /16.	11. /15.	11. /14.	10. /13.
E4 (Sq. Ft.)	15,840	7,690	5,120	4,180	3,620	2,890
E6 (Sq. Ft.)	1,820	950	660	560	560	560
E7 (Sq. Ft.)	33,120	15,300	8,000	6,430	5,600	4,590
P1 Make Up Horse-power (Stages)	**	500 (3)	3,100 (5)	5,000 (6)	7,200 (8)	12,000 (10)

* Linear Dimensions equal feet

** Primary Blower @ 700 hp.

TABLE IX

COMPRESSOR/EXPANDER

CHARACTERISTICS

PRESSURE (ATM)	HORSEPOWER (COMPRESSOR)	MAKE UP HORSEPOWER (COMP/EXPAND.)	OPERATING* COST/YEAR (COMP/EXPAND.)	OPERATING* COST/TON OF ACID
1	-	700**	42,000	.12
3	9,000	500	30,000	.086
5	15,000	3,100	186,000	.53
7	18,500	5,000	300,000	.86
9	22,000	7,200	432,000	1.23
13	29,000	12,000	726,000	2.08

* in Dollars

** Primary Blower @ 700 h.p.

TABLE X

EQUIPMENT COST,

($1000 UNITS)

EQUIPMENT	PRESSURE, ATM					
	(1)	(3)	(5)	(7)	(9)	(13)
T1	147	77	57	52	49	42
G1	191	102	73	55	46	35
E1	107	72	57	50	44	43
F2	46	15	10	9	8	7
R1	365	186	131	109	92	75
E5	43	25	64	53	52	51
E2	290	164	118	115	102	92
T2	157	83	61	56	53	45
E4	152	106	78	75	71	61
E6	39	28	22	20	20	20
E7	264	147	99	92	82	72
P1	52*	645	875	985	1,150	1,340
Sulfur Pit	50	50	50	50	50	50
Acid Pumps	90	90	90	90	90	90
Acid Cooler	138	138	138	138	138	138
Cooling Tower	500	500	500	500	500	500
Catalyst	660	195	116	83	46	44

* Priced as a conventional Primary Blower @ 700 hp

TABLE XI

FIXED CAPITAL VS PRESSURE

($1MM UNITS)

PRESSURE (ATM)	INVESTMENT (CATALYST FREE BASIS	CATALYST COST	TOTAL INSTALLED COST **	F.C. PRESSURE * / F.C. CONVENTIONAL
1	2.630	.660	3.421 *	1.18
3	2.427	.190	2.738	.95
5	2.427	.115	2.663	.92
7	2.447	.082	2.652	.915
9	2.546	.050	2.723	.94
13	2.663	.042	2.841	.98

** Based on Battery Limits including 5 percent contractor fee

* Conventional plant @ $2.9 MM

TABLE XII

ECONOMIC EVALUATION OF A

PRESSURE PLANT (1000 NT/DAY H_2SO_4)

PRESSURE (ATM)	TOTAL ** INVESTMENT ($ MM)	SALES ($ MM)	OPERATING COST (DOLLARS/TON)	GROSS INCOME ($ M)	PROFIT AFTER TAXES ($ M)	RETURN ON INVEST-MENT (PERCENT)	PAYOUT (YEARS) F.C./ (PROFIT + DEP.)
1 ***	4.075	5.954	15.20	938	219	5.38	5.7
3	3.913	5.954	15.066	994	247	6.32	5.25
5	3.838	5.954	15.61	804	152	3.96	6.37
7	3.827	5.954	15.94	604	52	1.36	8.4
9	3.898	5.954	16.31	554	27	.7	9.1

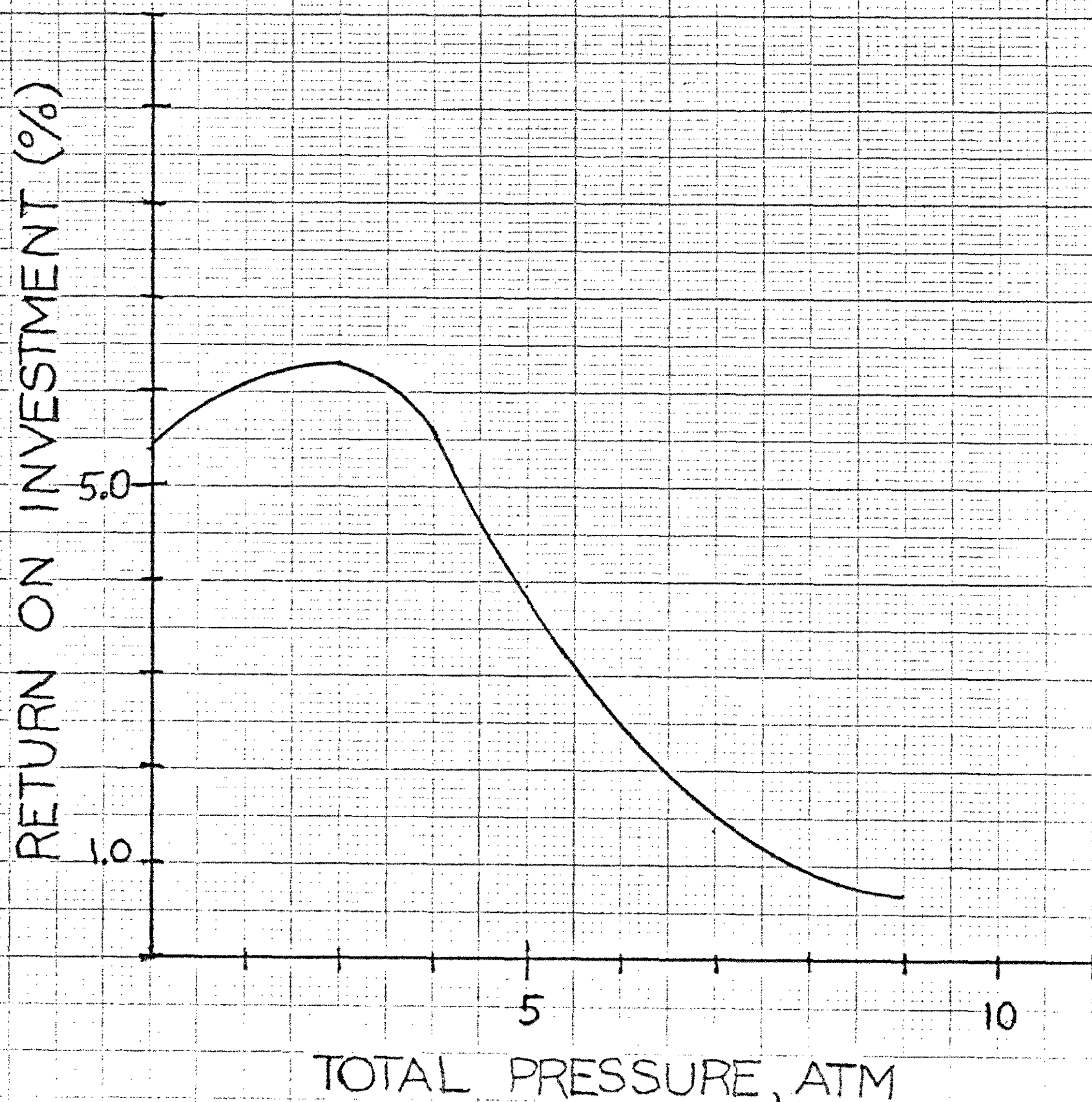
*** Economics Based on Conventional Plant for 1ATM.

* Gross Income Reduced by $500,000 Expenses & then taxed at 50 percent.

** Includes $1,175,000 working capital

FIG 12

RETURN ON INVESTMENT
VS
PRESSURE



CONCLUSIONS

1. The manufacture of sulfuric acid is economically attractive at pressures above one atmosphere but less than five atmospheres.

Operating pressures exceeding five atmospheres results in only slight improvements in fixed capital cost compared to rapidly rising operating cost.

2. The proposed pressure plant scheme is economically unattractive at one atmosphere compared with conventional plant economics developed by Kronseder [9].

3. A significant reduction in catalyst requirements is obtained at elevated pressures.

4. The compressor expander arrangement significantly reduces equipment cost, without prohibitive operating cost, for pressure ratios less than five. The gas expander reduces the required horsepower as much as twenty two times from that required by a motor driven centrifugal compressor.

RECOMMENDATIONS

Based on the results of this investigation, the following recommendations for further study are made:

1. An extention of this study that might be of interest would involve pressure plant designs at higher conversions and reduced SO_2 pollution.

2. Improvements in the equilibrium conversion characteristics, with pressure, allows operating at higher sulfur dioxide concentrations. The effect of gas concentration on plant economics could also be studied for pressure plants.

3. Other pressure plant equipment arrangements could be studied to determine optimum economy.

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NOMENCLATURE

A	=	Heat exchanger surface area, sq. ft.
Appch	=	Approach to equilibrium, y axis of of equil. conversion graph
A_X	=	Cross sectional Area, sq. ft.
a	=	Correlation factor, equat. (37), deminsionless
a_o	=	Dimensionless constant, a function of physical properties, .31
a_3, a_4	=	Dimensionless constant equal .023 and .33 respectively (turbulent)
a_i	=	Dimensionless constant equal .055 a function of tube arrangement
B_i	=	Dimensionless term defined by equation (46) for tubes
B_o	=	Dimensionless term defined by equation (47) for shell
C	=	Coefficient equal $(W_3/W_1)(n_c)(n_e)(R_3T_3/R_1T_1)$
C_{Ai}	=	Hourly fixed charges on equipment, \$/hr. ft.^{2} (inside area)
C_e	=	Cost of mechanical energy supplied to fluid, \$/ft. - lb.
C_p	=	Mean specific heat, Btu/lb - deg. F
C_p^*	=	Mean specific heat, Btu/lb - deg. F for component i
COFA	=	Coefficient of T^2, Btu/(deg F)^2
COFB	=	Coefficient of T, Btu/(deg F)

C_{SO_3}, C_{SO_2} C_{O_2}	=	Concentration of reaction components, moles
D	=	Tube diameter, Ft
D_P	=	Average particle size, Ft
E	=	Make-up horsepower, hp
e	=	Log constant = 2.718 - - - - -
Eff	=	Efficiency of operating plant based on sulfur
F_S	=	Safety factor, deminsionless
F	=	Feed, equivalent tons H_2SO_4/day
F_d, F_P, F_M	=	Correction factors to adjust capital cost as a result of design, pressure or material considerations, dimensionless
f_M	=	Friction factor define by equation (37)
G_{io}, G_{oo}	=	Optimum mass velocities tubes and shell respectively, (lb/hr. - sq. ft.)
G_o	=	Superficial mass velocity, #/Hr. - sq. ft.
g	=	Gas flow rate, #/sec.
G	=	Superficial mass velocity based on empty shell, lb/sec. - sq. ft.
g_c	=	Gravitational constant, 4.17 x 10^8 (lb fluid) (ft)/(hr) (hr) (lb_f)
H_{LOSS}	=	Heat loss to atmosphere by radiation, Btu/min
h	=	Individual heat transfer coefficient Btu/hr. - sq. ft.
Index	=	Cost index to update equipment cost, dimensionless

J	=	Stage or bed in converter
k'	=	Ratio of specific heats, C_p/C_v, dimensionless
K_i	=	Dimensionless term defined by equation (49)
K_o	=	Dimensionless term defined by equation (50)
k	=	Thermal conductivity, Btu/(hr) (sq. ft.) (deg F per ft.)
K_1	=	.55 for single pass and turbulent flow
$K_{Eq.}$	=	Equilibrium constant, dimensionless
k^*	=	Velocity constant define for Eklund equation
K_γ, K_ϕ, K_p	=	Equilibrium constants developed for overall conversion
L	=	Depth of bed, feet
L_H	=	Tube length, feet
l	=	Liquid flow rate, #/sec.
m_o, m_i'	=	Exponents dimensionless defined in equation (49) & (50) equal to .15 and .20 respectively
m'	=	Numerical value defined in equation (38)
m_i	=	Moles of component i
η_e	=	Efficiency of expander
η_c	=	Efficiency of compressor
n'	=	Numerical value defined in equation (38)

N	=	Number of tubes
n_i, N_o	=	Exponents defined in equations (53) & (54)
N_{TP}	=	Number of tube passes
O	=	Numerical value defined for equation (38)
P_{O_2}, P_{SO_2}, P_{SO_3}	=	Partial pressures of O_2, SO_2, SO_3 respect, psia
P, Press	=	Pressure, psia
Q	=	Heat transfer, Btu/hr
QSF	=	IBM scientific subprogram for intergration
RAT	=	Acid production, Tons Acid/Day
Re	=	Reynold's number, dimensionless
R	=	Gas constant, various dimensions
RH	=	Relative humidity
r	=	Reaction rate, Tons H_2SO_4 produced/ton catalyst - day
SENHT	=	Enthalpy of stream, Btu
SO2CN	=	SO_2 fractional concentration
T, Temp	=	Temperature, ^oK
TEMPK	=	Temperature, ^oK
t	=	Average liquid temperature for interval, ^oF
T'	=	Average gas temperature for interval, ^oF
T_{EQUIL}	=	Equilibrium temperature, ^oK
t_2, t_1	=	Bulk temperature, deg F

U	=	Overall heat transfer coefficient, Btu/(hr) (sq. ft.) ^{o}F
$w_{A,B}$	=	Tons of catalyst
$\dot{w}$	=	Mass flow, #/sec.
X	=	Fractional conversion
X'	=	Unit fractional conversion
X_{OVAL}	=	Overall fractional conversion
y_i	=	Mole fraction of component i
$y_{SO_3}, y_{SO_2}, y_{O_2}$	=	Mole fraction of respective components
y_o	=	Clearence between outer tube surface in a bundle, feet
α, β, γ	=	Coefficients of heat capacity equation defined in equation (6)
Δ	=	Incremental conversion
Δt	=	Mean value of temperature drop across individual thermal resistance, ^{o}F
Δt_m	=	Mean overall temperature drop from hot to cold fluid, deg. F.
ΔP^*	=	Pressure drop, inch H_2O/ft.
ρ	=	Density of fluid, lbs per cu. ft.
ξ	=	Normalized Pressure, P/14.7
θ	=	Normalized Temperature, T/520
ΔP	=	Pressure drop, Psi
$\Delta\alpha, \Delta\beta, \Delta\gamma$	=	Heat capacity coefficients used in H_{RXN} adjusting for stiochemetry.

ΔH_{RXN}	=	Heat of reaction, Btu/# mole
ΔT_{lm}	=	Log mean temperature difference
π	=	Total pressure, ATM
η, μ', ξ', m	=	Equation to define velocity constant eq. (34)
ϕ_i	=	Dimensionless term, a function of temperature
μ	=	Fluid viscosity, lbs/(hr) (ft)

APPENDIX A - SAMPLE PROBLEMS

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1. Equipment Estimates

Preliminary cost estimate for reactor, R1

Operating pressure	1 atm
Design parameters	29.2' diam. x 52.8' 473 tons of catalyst 3 beds in converter

Using Figure 5 in Guthrie, [7] the base cost for a pressure vessel is read. (Vertical arrangement).

a) Base cost = $83,000

The fraction of the converter vessel with an aluminum alloy is calculated from a ratio of catalyst in the top bed to total catalyst. Fm, the material correction factor is calculated:

$$\frac{18 \text{ Tons}}{473} = 5.3\%$$

Fm = 1.0 (c - steel)

Fm = 2.33 (Aluminum Alloy)

Fm = 94.7 x 1 + 5.3 x 2.33

Fm = 1.07

Fp = 1.0 for pressure to 50 psig

Index = 1.08 to correct cost from mid-1968 to mid-1970.

b) Expected cost mid 70 = (Fm * Fp * Index) * Base = 1.16 * Base = $93,000, F.O.B. Cost

Using the bare modual factor developed by Guthrie for vertical tank under $200,000.

c) Bare Modual Cost = Base * Bare Mod. Factor = 4.24 * 83,000 = $352,000.

d) Due to design changes to base equipment an additional $(93,000 - 83,000) = $10,000 is added.

Total Bare Modual Cost = 352,000 + 10,000 = $362,000

Other equipment are estimated on a similar basis using graph and factors developed by Guthrie.

2. <u>Make up Horsepower for Compressor - Expander</u>

Using equation developed by Canova [3] the make up horsepower is calculated from material flows and physical properties.

For a pressure ratios equal to 3.0:

$$\frac{E}{\sqrt{\theta_1}\,\xi_1} = \left[\frac{50.3\left(\omega_1\sqrt{\theta_1}/\xi_1\right)}{\eta_c}\right] * \left[\ln\frac{P_2}{P_1} - C\left(\frac{K'}{K'-1}\right)\left(1-\frac{P_3P_2}{P_2P_1}\right)^{-\frac{K'-1}{K'}}\right]$$

$$\theta_1 = \frac{T_1}{520} = 1.0 \text{ @ } T_1 = 60^\circ F$$

$$\delta_1 = P_1/14.7 = 1.0 \text{ @ } P_1 = 14.7$$

$$\omega_1 = \frac{79{,}300}{359} * \frac{29.9}{60} \quad 110 \ \#/\text{SEC}$$

$$K' = C_p/C_v = 1.401$$

$$\left(P_2/P_1\right)^{(K'-1/K')} = 1.365$$

$$\omega_3 = .90\,\omega_1$$

$$C = \frac{\omega_3}{\omega_1}\,\eta_c\eta_E\,\frac{R_3T_3}{R_1T_1} = (.90)(.65)(.85)\left(\frac{1460}{520}\right)$$

$$= 1.390$$

$$P_3 = .90\,P_2 \quad (\text{ASSUMED})$$

$$\left(P_3/P_1\right)^{-\frac{K'-1}{K'}} = .75$$

$$E = (50.3)(110)\left\{\frac{1.365 - 1.0 - (1.390)(.25)}{(.65)(.285)}\right\}$$

$$E = 510 \text{ hp}$$

3. Income Statement - Calculations - P = 3 ATM

Investment

Fixed Capital (From preliminary cost estimates for 3 ATM)	$ 2,738,000
Working Capital (Assumed identical for the conventional plant operating at same basis)	$ 1,175,000
(A) Total Investment (F. C. + W. C.)	$ 3,913,000

Income

(B) Sales 330,000 T.P.Y. @ $18.03/Ton	$ 5,954,000
Operating Cost @ $15.066 (Adjusted for power cost due to expander)	$ 4,960,000
(C) Gross Income	
Sales - Operating Cost	$ 994,000
All Other Expanses (Assumed equivalent to the conventional plant)	$ 500,000
Profit before Taxes	
Gross Income - Expenses =	$ 494,000
(D) Profit after Taxes @ 50% =	$ 247,000
Capital Turnover (B/A)	1.52
Gross Return on Sales (C/B)	16.7%

(D) continued

Return on Investment (D/A) ------ 6.32%

$$\text{Payout} = \frac{\text{F. C.}}{(\text{D+ Depreciation})} = 5.25 \text{ years}$$

APPENDIX B - COMPUTER PROGRAM

M87, M88, N88, N89, N90

N87

```
      COMMONIC                                                          N87 0010
      IC = 1                                                            N87 0020
      CALL LINK(M88)                                                    N87 0030
      END                                                               N87 0040
*STORE                                                                  N87 0050
```

This subprogram is used for initialization of iteration sequence in subprograms M88 and N88.

SUB PROGRAM M88 - HEAT AND MATERIAL BALANCE

STATEMENT NOS.	DESCRIPTION
10 / 290	Initialization of Balance
300 / 410	Overall Material Balance
420 / 690	Heat Duty on E 1
700 / 750	Loop Initialization for Converter
780 / 890	Compositions of Components
900 / 1230	Incremental Heat Balance Around Converter
1240 / 1300	Rate Expression
1310 / 2550	Catalyst Requirements
2560 / 2730	Call Link to N 88

```
M88  PAGE 1
      DEFINEFILE8(10,40,U,I8) ,9(1,40,U,I9)                           M88 0010
      DIMENSIONACIDM(11) ,H2OM(11) ,TOTM(11) ,SO2M(11) ,ZN2M(11) ,O2M(11M88 0020
     1) ,TEMPK(11) ,X(7) ,SO3M(11) ,TXSO2(90) ,Y(90) ,Z(90) ,WTCAT(90) ,M88 0030
     2VAT(8)                                                          M88 0040
      COMMONIC                                                        M88 0050
      GOTO(5,30),IC                                                   M88 0060
[redacted]
    5 DO   I=1,11                                                     M88 0070
      ACIDM(I) = 0.0                                                  M88 0080
      H2OM(I) = 0.0                                                   M88 0090
      TOTM(I) = 0.0                                                   M88 0100
      SO2M(I) = 0.0                                                   M88 0110
      ZN2M(I) = 0.0                                                   M88 0120
      O2M(I) = 0.0                                                    M88 0130
      TEMPK(I) = 0.0                                                  M88 0140
      SO3M(I) = 0.0                                                   M88 0150
   10 CONTINUE                                                        M88 0160
      WRITE(3,15)                                                     M88 0170
   15 FORMAT(1X,'PRESSURE SURFURIC ACID PLANT ')                      M88 0180
      WRITE(3,20)                                                     M88 0190
   20 FORMAT(/// ' HEAT + MATERIAL BALANCE')                          M88 0200
      WRITE(3,25)                                                     M88 0210
   25  FORMAT(/////' REACTOR DESIGN CONDITIONS')                      M88 0220
      RAT = 1000.                                                     M88 0230
      SO2CN = .08                                                     M88 0240
      EFFCY = .95                                                     M88 0250
      APPCH = .95                                                     M88 0260
      RH = .50                                                        M88 0270
      XOVAL = .99                                                     M88 0280
      PRESS = - 1.0                                                   M88 0290
      DO 245 IJ=1,6                                                   M88 0300
      PRESS = PRESS + 2.0                                             M88 0310
      ACIDP = RAT * 1.3888 / EFFCY                                    M88 0320
      H2OP = ACIDP * .02041                                           M88 0330
      ACIDM(6) = ACIDP / 98.                                          M88 0340
      H2OM(6) = H2OP / 18.                                            M88 0350
      TOTM(6) = ACIDM(6) + H2OM(6)                                    M88 0360
      TEMPK(6) = 311.                                                 M88 0370
      TOTM(7) = ACIDM(6) / SO2CN                                      M88 0380
      SO2M(7) = TOTM(7) * SO2CN                                       M88 0390
      ZN2M(7) = TOTM(7) * .79                                         M88 0400
      O2M(7) = TOTM(7) * (.21 - SO2CN)                                M88 0410
      TEMPK(8) = 723.                                                 M88 0420
      TEMPK(7) = 800.                                                 M88 0430
   30 TEMPK(7) = TEMPK(7) + 20.                                       M88 0440
      QN2 = ZN2M(7) * (11.743 * TEMPK(7) + .1125E - 02 * TEMPK(7) * * 2.M88 0450
     1 - 3599.)                                                       M88 0460
      QO2 = O2M(7) * (11.066 * TEMPK(7) + .2792E - 02 * TEMPK(7) * * 2. M88 0470
      QSO2 = SO2M(7) * (12.809 * TEMPK(7) + .8561E - 02 * TEMPK(7) * * 2M88 0480
     1. - 4578.)                                                      M88 0490
      QTOT = QN2 + QO2 + QSO2                                         M88 0500
      QN2 = ZN2M(7) * (11.743 * TEMPK(8) + .1125E - 02 * TEMPK(8) * * 2.M88 0510
     1 - 3599.)                                                       M88 0520
      QO2 = O2M(7) * (11.066 * TEMPK(8) + .2792E - 02 * TEMPK(8) * * 2. M88 0530
      QSO2 = SO2M(7) * (12.809 * TEMPK(8) + .8561E - 02 * TEMPK(8) * * 2M88 0540
     1. - 4578.)                                                      M88 0550
      QTOTB = QN2 + QO2 + QSO2                                        M88 0560
      Q = QTOT - QTOTB                                                M88 0570
      TOTP = Q / 825.1                                                M88 0580
      TEMPK(11) = 478.                                                M88 0590
```

M88 PAGE 2

```
      O2M(11) = 0.0
      TOTM(11) = TOTP / 18.
      H2OM(11) = TOTM(11)
      TOTM(8) = TOTM(7)
      SO2M(8) = SO2M(7)
      O2M(8) = O2M(7)
      ZN2M(8) = ZN2M(7)
      NJ = 1
      X(1) = 0.0
      SENHT = QTOTB
      ZN2 = ZN2M(8)
      TO2 = O2M(8)
      TSO2 = SO2M(8)
      XSO2 = - .01
      TEMP = TEMPK(8)
      ADD = .01
      DO 210 J=1,10
      DO 105 I=1,99
      XSO2 = XSO2 + ADD
      TXSO2(I) = XSO2
      SO3 = TSO2 * XSO2
      SO2 = TSO2 - SO3
      O2 = TO2 - .5 * SO3
      ZN2 = ZN2
      TOT = SO3 + SO2 + O2 + ZN2
      SO2MF = SO2 / TOT
      SO3MF = SO3 / TOT
      O2MF = O2 / TOT
      ZN2MF = ZN2 / TOT
      SO2X = TSO2 * ADD
      TKP = SO3MF / (SO2MF * O2MF * * .5 * PRESS * * .5)
      IF (TKP - .001) 35,35,40
   35 TMEQ = 3000.
      GOTO 45
   40 TLGKP = ALOG(TKP)
      DIV = ALOG(10.)
      TLGKP = TLGKP / DIV
      TMEQ = 4956. / (TLGKP + 4.678)
   45 IF (I - 1) 50,50,55
   50 SO2X = 0.0
      ROOT = TEMP
      GOTO 75
   55 HRXN = SO2X * ( - 43049. - 4.115 * TEMP + .6236E - 02 * TEMP * * 2
     1. - .1246E - 05 * TEMP * * 3.)
      COFA = ZN2 * .1125E - 02 + O2 * .2792E - 02 + SO2 * .8561E - 02 +
     1SO3 * .2118E - 01
      COFB = ZN2 * 11.743 + O2 * 11.066 + SO2 * 12.809 + SO3 * 10.939
      HLOSS = 0.0
      CONST = - 3599. * ZN2 - 3546. * O2 - 4578. * SO2 - 5141. * SO3
      COFC = HRXN - SENHT - HLOSS + CONST
      DISCR = SQRT(COFB * * 2. - 4. * COFA * COFC)
      ROOT = ( - COFB + DISCR) / (2. * COFA)
      IF (ROOT) 60,60,65
   60 ROOT = ( - COFB - DISCR) / (2. * COFA)
      IF (ROOT) 70,70,65
   65 IF (ROOT - 2000.) 75,75,70
   70 CONTINUE
C     ERROR 1
   75 TEMP = ROOT
      QN2 = ZN2 * (11.743 * TEMP + .1125E - 02 * TEMP * * 2. - 3599.)
      QO2 = O2 * (11.066 * TEMP + .2792E - 02 * TEMP * * 2. - 3546.)
```

M88 page 3

CALDERBANK'S EQUATION

```
      QSO2 = SO2 * (12.809 * TEMP + .8561E - 02 * TEMP * * 2. - 4578.)
      QSO3 = SO3 * (10.939 * TEMP + .2118E - 01 * TEMP * * 2. - 5141.)
      SENHT = QN2 + QO2 + QSO2 + QSO3
      EXPO1 = ( - 15600. / TEMP) + 12.07
      EXPO2 = ( - 26970. / TEMP) + 22.75
      AB = EXP(1.)
      RATE = 8.5E + 06 * ( ( (AB * * EXPO1 * O2MF * SO2MF / SO2MF * * .5
     1) * PRESS * * 1.5) - ( (AB * * EXPO2 * SO3MF * O2MF * * .5 / SO2MF
     2 * * .5) * PRESS))
      Y(I) = 1. / RATE
      IF (ABS(XSO2 - XOVAL) - .0001) 110,110,80
   80 IF (TMEQ - TEMP) 110,85,85
   85 CONTINUE
      IF (ABS(XSO2 - .90) - .0001) 90,105,105
   90 IF (ABS(XSO2 - .901) - .0001) 105,95,95
   95 CONTINUE
      NDIM = I
      H = ADD
      CALL QSF(H,Y,Z,NDIM)
      DO 100 K=1,NDIM
      WTCAT(K) = Z(K) * RAT
  100 CONTINUE
      CAT = WTCAT(NDIM)
      ADD = .001
  105 CONTINUE
  110 I = I - 1
      IF (ABS(XSO2 - XOVAL) - .0001) 170,170,115
  115 WRITE(3,120)J
  120 FORMAT(// 22H MAX. CONVERSION STAGE I4)
      WRITE(3,125)XSO2
  125 FORMAT(/17H MAX. CONVERSION=F8.5)
      RANGE = XSO2 - X(J)
      DESG = APPCH * RANGE
      XSO2 = DESG + X(J)
      N = I
      DO 130 L=1,N
      IF (XSO2 - TXSO2(L)) 135,130,130
  130 CONTINUE
  135 I = I - 1
      XSO2 = TXSO2(I)
      WRITE(3,140)XSO2
  140 FORMAT(/19H DESIGN CONVERSION=F8.5)
      JJ = J + 1
      X(JJ) = XSO2
      XRANG = (1.0 - APPCH) * RANGE * TSO2
      HRXN = XRANG * ( - 41697. - 4.113 * TEMP + .6236E - 02 * TEMP * *
     12. - .1246E - 05 * TEMP * * 3.)
      WSO3 = SO3 - XRANG
      WSO2 = SO2 + (SO3 - WSO3)
      WO2 = O2 + .5 * (SO3 - WSO3)
      WZN2 = ZN2
      COFA = WZN2 * .1125E - 02 + WO2 * .2792E - 02 + WSO2 * .8561E - 02
     1 + WSO3 * .2118E - 01
      COFB = WZN2 * 11.743 + WO2 * 11.066 + WSO2 * 12.809 + WSO3 * 10.93
     19
      CONST = - 3599. * WZN2 - 3546. * WO2 - 4578. * WSO2 - 5141. * WSO3
      HLOSS = 0.0
      COFC = - HRXN - SENHT - HLOSS + CONST
      DISCR = SQRT(COFB * * 2. - 4 * COFA * COFC)
      ROOT = ( - COFB + DISCR) / (2. * COFA)
      IF (ROOT) 145,145,150
```

M88 page 4

```
145 ROOT = ( - COFB - DISCR) / (2. * COFA)
    IF (ROOT) 155,155,150
150 IF (ROOT - 2000.) 160,160,155
155 CONTINUE
C   ERROR 2
160 TEMP = ROOT
    WRITE(3,165)TEMP
165 FORMAT(/26H DESIGN CONV. TEMPERATURE=F6.0)
    GOTO 175
170 I = I - 1
175 NDIM = I
    H = ADD
    CALL QSF(H,Y,Z,NDIM)
    DO 180 K=1,NDIM
    WTCAT(K) = Z(K) * RAT
180 CONTINUE
    WTCAT(NDIM) = WTCAT(NDIM) + CAT
    VAT(J) = WTCAT(NDIM)
    WRITE(3,185)J,WTCAT(NDIM),XSO2
185 FORMAT(    /7H STAGE I3,2X,9HCATALYST=F8.4,4X,5HXSO2=F8.5)
    CAT = 0.0
    IF (ABS(XSO2 - XOVAL) - .0001) 215,215,190
190 TTEMP = TEMP
    QBN2 = WZN2 * (11.743 * TEMP + .1125E - 02 * TEMP * * 2. - 3599.)
    QBO2 = WO2 * (11.066 * TEMP + .2792E - 02 * TEMP * * 2. - 3546.)
    QBSO2 = WSO2 * (12.809 * TEMP + .8561E - 02 * TEMP * * 2. - 4578.)
    QBSO3 = WSO3 * (10.939 * TEMP + .2118E - 01 * TEMP * * 2. - 5141.)
    TOTQ = QBN2 + QBO2 + QBSO2 + QBSO3
    TEMP = 673.
    QBN2 = WZN2 * (11.743 * TEMP + .1125E - 02 * TEMP * * 2. - 3599.)
    QBO2 = WO2 * (11.066 * TEMP + .2792E - 02 * TEMP * * 2. - 3546.)
    QBSO2 = WSO2 * (12.809 * TEMP + .8561E - 02 * TEMP * * 2. - 4578.)
    QBSO3 = WSO3 * (10.939 * TEMP + .2118E - 01 * TEMP * * 2. - 5141.)
    TOTQA = QBN2 + QBO2 + QBSO2 + QBSO3
    A = TOTQ - TOTQA
    IF (J - 1) 195,195,200
195 ZN2M(9) = WZN2
    O2M(9) = WO2
    SO3M(9) = WSO3
    SO2M(9) = WSO2
    TOTM(9) = ZN2M(9) + O2M(9) + SO3M(9) + SO2M(9)
    TEMPK(9) = TTEMP
    ZN2M(10) = ZN2M(9)
    O2M(10) = O2M(9)
    SO3M(10) = SO3M(9)
    SO2M(10) = SO2M(9)
    TOTM(10) = TOTM(9)
    TEMPK(10) = 673.
    SENHT = TOTQA
    GOTO 205
200 R = A / 5972.
    ZN2M(NJ) = R
    O2M(NJ) = R * .266
    TOTM(NJ) = ZN2M(NJ) + O2M(NJ)
    NJ = NJ + 1
    ZN2 = ZN2 + R
    TO2 = WO2 + .266 * R
    QBN2 = ZN2 * (11.743 * TEMP + .1125E - 02 * TEMP * * 2. - 3599.)
    QBO2 = TO2 * (11.066 * TEMP + .2792E - 02 * TEMP * * 2. - 3546.)
    QSO2 = WSO2 * (12.809 * TEMP + .8561E - 02 * TEMP * * 2. - 4578.)
    QSO3 = WSO3 * (10.939 * TEMP + .2118E - 01 * TEMP * * 2. - 5141.)
```

M88 PAGE 5

```
      SENHT = QBN2 + QBO2 + QSO2 + QSO3
  205 XSO2 = XSO2 - ADD
  210 CONTINUE
  215 WRITE(3,220)J
  220 FORMAT(/ /24H FINAL CONVERSION STAGE I3)
      WRITE(3,225)TEMP
  225 FORMAT(/ 13H FINAL TEMP.=F7.1)
      WRITE(3,230)XSO2
  230 FORMAT(/15H FINAL CONVER.=F8.5)
      NJ = NJ + 38
      TT = J
      WRITE(3,235)
  235 FORMAT(//// ' POLUTION EMISSION')
      PPM = (SO2 * 64. / (SO2 * 64. + O2 * 32. + ZN2 * 28. + SO3 * 80.))
     1* 1000000.
      WRITE(3,240)PPM
  240 FORMAT(1X, 9HEXIT SO2=F8.2)
  245 CONTINUE
      WRITE(9'1) SO3,SO2,O2,ZN2,TOT,TEMP,RH,RAT,Q,A,PRESS,NJ,TT
      WRITE(8'1) TEMPK
      WRITE(8'2) H2OM
      WRITE(8'3) TOTM
      WRITE(8'4) SO2M
      WRITE(8'5) ZN2M
      WRITE(8'6) O2M
      WRITE(8'7) ACIDM
      WRITE(8'8) SO3M
      WRITE(8'9) VAT
      CALL LINK(N88)
      END
*STORE
```

M88 PAGE 6

Eklund Rate Equation

```
ELOGK = 4956./TEMP - 4.678
TKPE = 10. ** ELOGK
C1 = 0.4248762 E-02
C2 = -0.1471751 E-04
C3 = 0.1411377 E-07
C4 = -0.3580165 E-14
TK = C1 + C2 * TEMP + C3 * TEMP ** 2
        + C4 * TEMP ** 4
RATE = 8.5 E+06 * TK * (SO2MF/SO3MF)
        ** .5 * (O2MF * PRESS -
        (SO3MF/(SO2MF * TKPE)) ** 2)
```

SUBPROGRAM N88 - HEAT AND MATERIAL BALANCE

STATEMENT NOS.	DESCRIPTION
10 / 250	Initialization
260 / 690	Balance Around E 1, E 2
700 / 1570	Balance Around T 1
1580 / 1740	Balance Around T 2
1750 / 2740	Balance all Streams
2750 / 2960	Call Link to N 89

N 88 page 1

```
      DEFINEFILE8(10,40,U,I8) ,9(1,40,U,I9) ,7(10,90,U,I7)
      DIMENSIONSM(45) ,ACIDM(45) ,H2OM(45) ,TOTM(45) ,SO2M(45) ,ZN2M(45)
     1,O2M(45) ,TEMPK(45) ,SO3M(45) ,VAT(8)
      DO 5 I=1,45
      SM(I) = 0.0
      ACIDM(I) = 0.0
      H2OM(I) = 0.0
      TOTM(I) = 0.0
      SO2M(I) = 0.0
      ZN2M(I) = 0.0
      O2M(I) = 0.0
      TEMPK(I) = 0.0
      SO3M(I) = 0.0
    5 CONTINUE
      READ(9'1) SO3,SO2,O2,ZN2,TOT,TEMP,RH,RAT,Q,A,PRESS,NJ,TT
      READ(8'6) (O2M(I) ,I = 40,44) ,O2M(18) , (O2M(I) ,I = 7,11)
      READ(8'9) (VAT(I) ,I = 1,8)
      READ(8'1) (TEMPK(I) ,I = 40,44) ,TEMPK(18) , (TEMPK(I) ,I = 7,11)
      READ(8'7) (ACIDM(I) ,I = 40,44) ,ACIDM(18) , (ACIDM(I) ,I = 7,11)
      READ(8'2) (H2OM(I) ,I = 40,44) ,H2OM(18) , (H2OM(I) ,I = 7,11)
      READ(8'3) (TOTM(I) ,I = 40,44) ,TOTM(18) , (TOTM(I) ,I = 7,11)
      READ(8'8) (SO3M(I) ,I = 40,44) ,SO3M(18) , (SO3M(I) ,I = 7,11)
      READ(8'5) (ZN2M(I) ,I = 40,44) ,ZN2M(18) , (ZN2M(I) ,I = 7,11)
      READ(8'4) (SO2M(I) ,I = 40,44) ,SO2M(18) , (SO2M(I) ,I = 7,11)
      WRITE(3,10)
   10 FORMAT(///' HEAT EXCHANGER DUTY')
      WRITE(3,15)Q
   15 FORMAT(//18H HEAT DUTY ON E-1=E12.4)
      SO3M(12) = SO3
      SO2M(12) = SO2
      O2M(12) = O2
      ZN2M(12) = ZN2
      TOTM(12) = TOT
      TEMPK(12) = TEMP
      SM(6) = ACIDM(18)
      TOTM(6) = SM(6)
      TEMPK(6) = 400.
      O2M(4) = TOTM(7) * .21
      ZN2M(4) = TOTM(7) * .79
      H2OM(4) = TOTM(7) * 359. * 1. / (1000. * 454. * 18.)
      TOTM(4) = O2M(4) + ZN2M(4) + H2OM(4)
      NJJ = NJ
      NY = NJ - 39
      NJ = 39
      DO 20 KK=1,NY
      NJ = NJ + 1
      ZN2M(5) = ZN2M(NJ) + ZN2M(5)
      O2M(5) = O2M(NJ) + O2M(5)
   20 CONTINUE
      TOTM(5) = ZN2M(5) + O2M(5)
      H2OM(5) = H2OM(4) * (TOTM(5) / TOTM(4))
      TOTM(5) = TOTM(5) + H2OM(5)
      QCN2 = ZN2M(12) * (11.743 * (TEMPK(12) - 505.) + .1125E - 02 * (TE
     1MPK(12) * * 2. - 505. * * 2))
      QCO2 = O2M(12) * (11.066 * (TEMPK(12) - 505.) + .2792E - 02 * (TEM
     1PK(12) * * 2. - 505. * * 2))
      QCSO2 = SO2M(12) * (12.809 * (TEMPK(12) - 505.) + .8561E - 02 * (T
     1EMPK(12) * * 2. - 505. * * 2))
      QCSO3 = SO3M(12) * (10.939 * (TEMPK(12) - 505.) + .2118E - 01 * (T
     1EMPK(12) * * 2. - 505. * * 2))
```

N88 page 2

```
      B = QCN2 + QCO2 + QCSO2 + QCSO3
      WRITE(3,25)B
   25 FORMAT(//18H HEAT DUTY ON E-2=E12.4)
      ZN2M(13) = ZN2M(12)
      O2M(13) = O2M(12)
      SO3M(13) = SO3M(12)
      SO2M(13) = SO2M(12)
      TOTM(13) = TOTM(12)
      TEMPK(13) = 505.
      O2M(3) = O2M(4) + O2M(5)
      ZN2M(3) = ZN2M(4) + ZN2M(5)
      H2OM(3) = H2OM(4) + H2OM(5)
      TOTM(3) = O2M(3) + ZN2M(3) + H2OM(3)
      O2M(2) = O2M(3)
      ZN2M(2) = ZN2M(3)
      TOTC = O2M(2) + ZN2M(2)
      H2OM(2) = RH * (23.756 / 760.) * TOTC
      TOTM(2) = O2M(2) + ZN2M(2) + H2OM(2)
      TEMPK(2) = 298.
      O2M(1) = O2M(2)
      ZN2M(1) = ZN2M(2)
      H2OM(1) = H2OM(2)
      TOTM(1) = TOTM(2)
      TEMPK(1) = TEMPK(2)
      H2OM(20) = ACIDM(18) + (ACIDM(18) * 98. * (.02 / .98)) / 18. - H2O
     1M(2)
      O2M(20) = 0.0
      ZN2M(20) = 0.0
      SO3M(20) = 0.0
      TOTM(20) = H2OM(20)
      TEMPK(20) = 298.
      ACIDM(19) = (RAT * 2.5 * 15.374 * .98) / 98.
      H2OM(19) = (ACIDM(19) * 98. * (.02 / .98)) / 18.
      TEMPK(19) = 311.
      TOTM(19) = ACIDM(19) + H2OM(19)
      H2OM(21) = H2OM(20) + H2OM(19)
      ACIDM(21) = ACIDM(20) + ACIDM(19)
      TOTM(21) = H2OM(21) + ACIDM(21)
      PCT = ACIDM(21) * 98. / (ACIDM(21) * 98. + H2OM(21) * 18.)
      HEAT = ( (1.0 - PCT) * 800. - 16.) * ACIDM(21) * 98.
      DELT = HEAT / ( (ACIDM(21) * 98. + H2OM(21) * 18.) * .35)
      T = 100. + DELT
      TEMPK(21) = (T - 32.) * (5. / 9.) + 273.
      NJ = NJJ
      NY = NJ - 39
      NJ = 39
      TEMPK(3) = TEMPK(21) - 1.
      DO 30 KK=1,NY
      NJ = NJ + 1
      TEMPK(NJ) = TEMPK(3)
   30 CONTINUE
      TEMPK(5) = TEMPK(3)
      TEMPK(4) = TEMPK(3)
      QDN2 = ZN2M(2) * (11.743 * (TEMPK(3) - 298.) + .1125E - 02 * (TEMP
     1K(3) * * 2. - 298. * * 2))
      QDO2 = O2M(2) * (11.066 * (TEMPK(3) - 298.) + .2792E - 02 * (TEMPK
     1(3) * * 2. - 298. * * 2))
      QDTOT = QDN2 + QDO2
      REF = (1.0 - PCT) * 800.
      AH2O = H2OM(2) * 18. - H2OM(3) * 18.
      PCT = (ACIDM(21) * 98.) / (ACIDM(21) * 98. + (H2OM(21) + H2OM(2))
```

N88 page 3

```
1* 18.)
 HEAT = ( (1.0 - PCT) * 800. - REF) * ACIDM(21) * 98.
 QAA = HEAT + QDTOT
 DELT = (QAA / ( (ACIDM(21) * 98. + H2OM(21) * 18. + H2OM(2) * 18.)
1* .35)) / 1.8
 TEMPK(22) = TEMPK(21) + DELT
 ACIDM(22) = ACIDM(21)
 H2OM(22) = H2OM(21) + H2OM(2)
 TOTM(22) = ACIDM(22) + H2OM(22)
 QRN = SO3M(13) * 80. * 697.
 TOTP = RAT * 2.5 * 15.2
 ACIDM(15) = (.98 * TOTP) / 98.
 H2OM(15) = (.02 * TOTP) / 18.
 TOTM(15) = ACIDM(15) + H2OM(15)
 ACIDM(16) = SO3M(13) + ACIDM(15)
 H2OM(16) = H2OM(15) - SO3M(13)
 TOTM(16) = ACIDM(16) + H2OM(16)
 ACIDM(17) = ACIDM(16) + ACIDM(22)
 H2OM(17) = H2OM(16) + H2OM(22)
 TOTM(17) = H2OM(17) + ACIDM(17)
 PCT = ACIDM(16) * 98. / (ACIDM(16) * 98. + H2OM(16) * 18.)
 HEAT = ( (1.0 - PCT) * 800. - 16.) * ACIDM(16) * 98.
 T1 = 100.
 DO 35 MN=1,300
 T1 = T1 + 1.0
 T22 = 1.8 * (TEMPK(22) - 273.) + 32.
 T2 = (T1 + T22) / 2.
 QN2 = ZN2M(13) * (11.743 * (505. - T2) + .1125E - 02 * (505. * * 2
1 - T2 * * 2))
 QO2 = O2M(13) * (11.066 * (505. - T2) + .2792E - 02 * (505. * * 2
 QSO2 = SO2M(13) * (12.809 * (505. - T2) + .8561E - 02 * (505. * *
12 - T2 * * 2))
 QE = QN2 + QO2 + QSO2
 QTOTB = QRN + HEAT + QE
 QTOTA = (ACIDM(16) * 98. + H2OM(16) * 18.) * .40 * (T1 - T2)
 SENTV = TOTP * .40 * 1.0 * 2.0
 IF (ABS(QTOTA - QTOTB) - SENTV) 40,40,35
35 CONTINUE
40 TEMPK(16) = .555 * (T1 - 32.) + 273.
 TEMPK(15) = .555 * (T2 - 32.) + 273.
 TEMPK(14) = TEMPK(15) + 1.0
 O2M(14) = O2M(13)
 ZN2M(14) = ZN2M(13)
 SO2M(14) = SO2M(13)
 SO3M(14) = 0.0
 TOTM(14) = O2M(14) + ZN2M(14) + SO2M(14)
 TEMPK(17) = TEMPK(15)
 TEMPK(36) = TEMPK(17)
 ACIDM(36) = ACIDM(17) - ACIDM(15)
 H2OM(36) = H2OM(17) - H2OM(15)
 TOTM(36) = ACIDM(36) + H2OM(36)
 TEM = (TEMPK(36) - 273.) * 1.8 + 32.
 QBB = (ACIDM(36) * 98. + H2OM(36) * 18.) * .4 * (TEM - 100.)
 WRITE(3,45)QBB
45 FORMAT(//18H HEAT DUTY ON E-3=E12.4)
 TOTM(33) = (QBB / (1. * 63.)) / 18.
 H2OM(33) = TOTM(33)
 TOTM(34) = TOTM(33)
 H2OM(34) = H2OM(33)
 TEMPK(33) = 298.
 TEMPK(34) = 333.
```

N88 PAGE A

```
      COFB = ZN2M(14) * 11.743 + O2M(14) * 11.066 + SO2M(14) * 12.809
      COFA = ZN2M(14) * .1125E - 02 + O2M(14) * .2792E - 02 + SO2M(14) *
     1.8561E - 02
      D = COFB * (TEMPK(14) - 298.) + COFA * (TEMPK(14) * * 2 - 298. * *
     12)
      COFC = - D - B - COFB * 298. - COFA * 298. * * 2
      DISCR = SQRT(COFB * * 2. - 4. * COFA * COFC)
      ROOT = ( - COFB + DISCR) / (2. * COFA)
      IF (ROOT) 50,50,55
   50 ROOT = ( - COFB - DISCR) / (2. * COFA)
      IF (ROOT) 60,60,55
   55 IF (ROOT - 3000.) 70,70,60
   60 WRITE(3,65)
   65 FORMAT(////19H ERROR IN PROGRAM 3)
   70 TEMPK(23) = ROOT
      TEMPK(24) = 813.
      QCN2 = ZN2M(14) * (11.743 * (TEMPK(24) - TEMPK(23)) + .1125E - 02
      QCO2 = O2M(14) * (11.066 * (TEMPK(24) - TEMPK(23)) + .2792E - 02 *
     1(TEMPK(24) * * 2. - TEMPK(23) * * 2))
      QCSO2 = SO2M(14) * (12.809 * (TEMPK(24) - TEMPK(23)) + .8561E - 02
     1 * (TEMPK(24) * * 2. - TEMPK(23) * * 2))
      C = QCN2 + QCO2 + QCSO2
      IF (ABS(C - Q) - 1000.) 75,75,80
   75 IC = 2
      CALL M88
   80 D = COFB * (TEMPK(23) - 298.) + COFA * (TEMPK(23) * * 2 - 298. * *
     12)
      COFC = - D - C - COFB * 298. - COFA * 298. * * 2
      DISCR = SQRT(COFB * * 2. - 4. * COFA * COFC)
      ROOT = ( - COFB + DISCR) / (2. * COFA)
      IF (ROOT) 85,85,90
   85 ROOT = ( - COFB - DISCR) / (2. * COFA)
      IF (ROOT) 95,95,90
   90 IF (ROOT - 3000.) 105,105,95
   95 WRITE(3,100)
  100 FORMAT(////19H ERROR IN PROGRAM 4)
  105 TEMPK(24) = ROOT
      TEMPK(37) = 1166.
      SO2M(37) = SO2M(7)
      O2M(37) = O2M(7)
      ZN2M(37) = ZN2M(7)
      TOTM(37) = TOTM(7)
      ZN2M(23) = ZN2M(14)
      O2M(23) = O2M(14)
      SO2M(23) = SO2M(14)
      TOTM(23) = TOTM(14)
      ZN2M(24) = ZN2M(14)
      O2M(24) = O2M(14)
      SO2M(24) = SO2M(14)
      TOTM(24) = TOTM(14)
      ZN2M(25) = ZN2M(14)
      O2M(25) = O2M(14)
      SO2M(25) = SO2M(14)
      TOTM(25) = TOTM(14)
      TEMPK(32) = 477.
      TEMPK(25) = TEMPK(24)
      TEMPK(26) = 508.
      TOTP = A / 825.1
      TEMPK(38) = 478.
      TOTM(38) = TOTP / 18.
      H2OM(38) = TOTM(38)
```

N88 page 5

```
      E = COFA * (TEMPK(25) * * 2. - TEMPK(26) * * 2.) + COFB * (TEMPK(2
     15) - TEMPK(26))
      WRITE(3,110)E
  110 FORMAT(//18H HEAT DUTY ON E-4=E12.4)
      WRITE(3,115)A
  115 FORMAT(//18H HEAT DUTY ON E-5=E12.4)
      H2OM(32) = (E / 825.1) / 18.
      TOTM(32) = H2OM(32)
      H2OM(29) = H2OM(32) + H2OM(11) + H2OM(38)
      TOTM(29) = TOTM(32) + TOTM(11) + TOTM(38)
      TEMPK(27) = 393.
      F = COFA * (TEMPK(26) * * 2. - TEMPK(27) * * 2.) + COFB * (TEMPK(2
     16) - TEMPK(27))
      WRITE(3,120)F
  120 FORMAT(//18H HEAT DUTY ON E-6=E12.4)
      WRITE(3,125)C
  125 FORMAT(// ' HEAT DUTY ON E7 = 'E12.4)
      TEMPK(29) = 298.
      H2OM(35) = H2OM(29)
      TOTM(35) = H2OM(35)
      DTT = (F / (H2OM(29) * 18. * 1.)) / 1.8
      TEMPK(35) = TEMPK(29) + DTT
      DO 130 L=26,28
      SO3M(L) = SO3M(14)
      ZN2M(L) = ZN2M(14)
      O2M(L) = O2M(14)
      SO2M(L) = SO2M(14)
      TOTM(L) = TOTM(14)
  130 CONTINUE
      TEMPK(28) = TEMPK(27)
      WRITE(3,135)
  135 FORMAT(/////' COMPOSITIONS + TEMPERATURES')
      WRITE(3,140)
  140 FORMAT(/1X, 6HSTREAM,2X,5HTEMPK,5X,4HZN2M,9X,3HO2M,10X,4HH2OM,10X,
     14HSO2M,7X,4HSO3M,8X,5HH2SO4,8X,2HSM,8X,4HTOTM)
      DO 150 KK=1,NJJ
      WRITE(3,145)KK,TEMPK(KK),ZN2M(KK),O2M(KK),H2OM(KK),SO2M(KK),SO3M(K
     1K),ACIDM(KK),SM(KK),TOTM(KK)
  145 FORMAT(4X,I3,3X,F5.0,2X,E10.4,7(3X,E10.4))
  150 CONTINUE
      WRITE(9'1) SO3,SO2,O2,ZN2,TOT,TEMP,RH,RAT,Q,A,PRESS,NJ,TT,QE,E,B,F
     1,C
      WRITE(7'1) TEMPK
      WRITE(7'2) H2OM
      WRITE(7'3) TOTM
      WRITE(7'4) SO2M
      WRITE(7'5) ZN2M
      WRITE(7'6) O2M
      WRITE(7'7) ACIDM
      WRITE(7'8) SO3M
      CALL LINK(N89)
      END
*STORE
```

SUBPROGRAM - N 89 - EQUIPMENT DESIGN

STATEMENT NOS.	DESCRIPTION
150 / 220	F 1 Design
210 / 950	T 1 Design
960 / 1060	G 1 Design
1070 / 1440	E 1 Design
1450 / 1560	F 2 Design
1570 / 1920	R 1 Design
1930 / 2200	E 5 Design
2230 / 2290	Call Link N 90

N89 PAG 1

```
      DEFINEFILE8(10,40,U,I8) ,9(1,40,U,I9) ,7(10,90,U,I7)
      DIMENSIONACIDM(45) ,H2OM(45) ,TOTM(45) ,SO2M(45) ,ZN2M(45) ,O2M(45
     1) ,TEMPK(45) ,SO3M(45) ,VAT(8) ,HIGH(8) ,PRES(20) ,Y(90) ,Z(90)
      READ(9'1) SO3,SO2,O2,ZN2,TOT,TEMP,RH,RAT,Q,A,PRESS,NJ,TT,OE,E,B,F,
     1C
      READ(7'1) (TEMPK(I) ,I = 1,45)
      READ(7'2) (H2OM(I) ,I = 1,45)
      READ(7'3) (TOTM(I) ,I = 1,45)
      READ(7'4) (SO2M(I) ,I = 1,45)
      READ(7'5) (ZN2M(I) ,I = 1,45)
      READ(7'6) (O2M(I) ,I = 1,45)
      READ(7'7) (ACIDM(I) ,I = 1,45)
      READ(7'8) (SO3M(I) ,I = 1,45)
      READ(8'9) (VAT(I) ,I = 1,8)
C     DESIGN OF AIR FILTER F1
      VOLM = TOTM(1) * 359. / PRESS
      WRITE(3,5)
    5 FORMAT(/////' **** DESIGN PARAMETERS FOR   F1')
      WRITE(3,10)VOLM
   10 FORMAT(//4X,' FILTER CAPACITY(ACFM)                  ='F7.0)
      WRITE(3,65)PRESS
C     DESIGN OF DRYING TOWER COLUMN T1
      DO 15 M=1,20
      PRES(M) = PRESS
   15 CONTINUE
      G = (ZN2M(2) * 28. + O2M(2) * 32. + H2OM(2) * 18.) / 60.
      TL = (RAT * 2.5 * 15.2) / 60.
      DENLL = 15.2 / .1337
      DENVV = 22. * PRES(1) / ( (TEMPK(2) + TEMPK(3)) / 2.)
      VISCL = 3.8
      COA = (TL / G) * (DENVV / DENLL) * * .5
      TM = .377E + 04 * COA + .754E + 03
      TN = .209E + 04 * COA + .880E + 03
      TLOAD = .50
      DELTP = 1.5 * TLOAD
      TO = DELTP / (TM * DELTP + TN)
      AREA = (G / DENLL) * (VISCL * * .2 / (DENVV * TO)) * * .5
      GO = G * 3600. / AREA
      COFJ = 1.06 * (.146 * GO / .046) * * ( - .41)
      PENO = (.24 * .046 / .0157) * * .666
      HH = COFJ * .24 * GO / PENO
      TF2 = (9. / 5.) * (TEMPK(2) - 273.) + 32.
      TF3 = (9. / 5.) * (TEMPK(3) - 273.) + 32.
      TF22 = (9. / 5.) * (TEMPK(22) - 273.) + 32.
      TF21 = (9. / 5.) * (TEMPK(21) - 273.) + 32.
      TEMRO = (TF3 - TF2) / (TF22 - TF21)
      TINCR = (TF3 - TF2) / 50.
      TEMG = TF2
      TEML = TF22
      DO 20 LM=1,50
      TEMG1 = TEMG
      TEMG = TEMG + TINCR
      TAVG = (TEMG1 + TEMG) / 2.
      TEML1 = TEML
      TEML = TEML - TINCR * (1. / TEMRO)
      TAVL = (TEML1 + TEML) / 2.
      DIFF = TAVL - TAVG
      RECP = 1. / DIFF
      Y(LM) = RECP
   20 CONTINUE
```

N89 page 2

```
      NDIM = 50
      H = TINCR
      CALL QSF(H,Y,Z,NDIM)
      NDIM = 50
      TINTR = Z(NDIM)
      TM2 = (O2M(2) * 32. + ZN2M(2) * 28. + H2OM(2) * 18.) * 60.
      TM3 = (O2M(3) * 32. + ZN2M(3) * 28. + H2OM(3) * 18.) * 60.
      TMAVG = (TM2 + TM3) / 2.
      CP = .24
      SAREA = (TINTR * TMAVG * CP) / HH
      THIGH = SAREA / (28. * AREA)
      THIGH = 1.333 * THIGH
      DIAM = SQRT(AREA / .785)
      IF (THIGH - 10.) 25,25,30
   25 THIGH = DIAM
   30 PAC = AREA * THIGH
      BEDS = THIGH / (3. * DIAM)
      NBEDS = BEDS + 1
      PRED = (.75 * THIGH + .30 * (.75 * THIGH)) / 12. * (14.7 / 34.)
      THIGH = THIGH + .30 * DIAM
      WRITE(3,35)
   35 FORMAT(/////' **** DESIGN PARAMETERS FOR   T1')
      WRITE(3,40)DIAM
   40 FORMAT(//4X,' DIAMETER(FT)                          ='F6.1)
      WRITE(3,45)THIGH
   45 FORMAT(1X,3X,' HEIGHT OR LENGHT(FT)                 ='F6.1)
      WRITE(3,50)PAC
   50 FORMAT(1X,3X,' PACKING (CU FT)                      ='F6.0)
      WRITE(3,55)NBEDS
   55 FORMAT(1X,3X,' NUMBER OF BEDS                       ='I3)
      WRITE(3,60)PRED
   60 FORMAT(1X,3X,' PRESSURE DROP INSIDE (PSI)           ='F5.1)
      WRITE(3,65)PRESS
   65 FORMAT(1X,3X,' PRESSURE(ATM)                        ='F5.0)
C     DESIGN OF SULFUR BURNER  G1
      VOLM = 40. * RAT * (32. / 98.) * (1. / PRES(2))
      DIAM = (VOLM / 1.18) * * .3333
      HT = 1.5 * DIAM
      PD = .5
      WRITE(3,70)
   70 FORMAT(/////' **** DESIGN PARAMETERS FOR   G1')
      WRITE(3,40)DIAM
      WRITE(3,45)HT
      WRITE(3,60)PD
      WRITE(3,65)PRESS
C     DESIGN OF BURNER COOLER E-1
      AVGTI = (TEMPK(7) + TEMPK(8)) / 2.
      DENSI = 22. * PRES(3) / AVGTI
      PHI = ( (TEMPK(7) - TEMPK(8)) / (AVGTI - 478.)) * .782
      BI = 1.0 + .00184 / PHI
      CI = .570E - 10 * BI / DENSI * * 2
      CEI = .750E - 08
      QQ = Q * 60.
      DT = (AVGTI - TEMPK(11)) * 1.8
      U = 1.0
      ENR = 800.
      DO 75 MM=1,100
      U = U + .3
      AREA = QQ / (U * DT)
      CA = (16000. * (AREA / 1000.) * * .88) / AREA * (ENR / 1000.)
      CAI = CA * .20 / 8300.
```

N 89 page 3

```
      RATIO = 1.0
      GIO = ( (CAI / (CEI * CI)) / (3.5 * RATIO - 1.)) * * .357
      HI = .555E - 02 * GIO * * .8
      REPV = 1. / HI
      V = 1. / REPV
      IF (ABS(U - V) - .5) 80,80,75
   75 CONTINUE
   80 FI = .055 * (.094 / ( (2.067 / 12.) * GIO)) * * .2
      PDP1 = (1.00248 * 4. * FI * 20. * GIO * * 2) / (2. * 4.17E + 08 *
     1DENSI * 2.067)
      WRITE(3,85)
   85 FORMAT(/////' **** DESIGN PARAMETERS FOR   E1')
      WRITE(3,90)QQ
   90 FORMAT(//4X,' HEAT EXCHANGE DUTY(BTU/HR)           ='E12.4)
      WRITE(3,95)U
   95 FORMAT(1X,3X,' HEAT TRANSFER COFF(BTU/SQ FT/DEG F)='F6.1)
      WRITE(3,100)DT
  100 FORMAT(1X,3X,' TEMPERATURE DIFFERENCE(DEG F)       ='F6.0)
      WRITE(3,105)AREA
  105 FORMAT(1X,3X,' SURFACE AREA(SQ FT)                 ='F7.0)
      WRITE(3,60)PDP1
      WRITE(3,65)PRESS
C     DESIGN OF HOT GAS FILTER  F2
      VOLM = TOTM(7) * (1.0 / PRES(4)) * 359.
      TUBES = VOLM / 2000.
      DIAM = 1.37 * TUBES * * .475 * 1.5
      HT = DIAM
      PD = .3
      WRITE(3,110)
  110 FORMAT(/////' **** DESIGN PARAMETERS FOR   F2')
      WRITE(3,40)DIAM
      WRITE(3,45)HT
      WRITE(3,60)PD
      WRITE(3,65)PRESS
C     DESIGN OF CONVERTER
      L = TT
      TOTCT = 0.0
      DO 115 LM=1,L
      VAT(LM) = (VAT(LM) + VAT(LM) * .15) * 2000.
      TOTCT = VAT(LM) + TOTCT
  115 CONTINUE
      TOTCT = TOTCT / 2000.
      VOLF = TOTM(8) * 359. / PRES(5)
      VOLF = VOLF * PRES(5) * * .5
      XAREA = VOLF / 100.
      DIAM = (XAREA / .785) * * .5
      HT = 0.0
      DO 120 LN=1,L
      HIGH(LN) = (VAT(LN) / 40.) / XAREA
      HT = HIGH(LN) + .15 * DIAM + HT
  120 CONTINUE
      TOTHT = HT + .15 * DIAM
      G = ( (ZN2M(8) * 28. + O2M(8) * 32. + SO2M(8) * 64.) / 60.) / XARE
     1A
      DP = .0525
      VISC = .286E - 04
      RENO = (DP * G) / VISC
      F = 79.5 / RENO * * .375
      DEN = 26.6 * (PRES(5) / TEMPK(9))
      DROP = (2. * F * G * * 2 * TOTHT) / (144. * DP * 32.2 * DEN)
      DROP = DROP + .20 * DROP
```

N89 Page 4

```
      PDRT = DROP * (VAT(1) / (VAT(1) + VAT(2) + VAT(3) + VAT(4)))
      WRITE(3,125)
  125 FORMAT(/////' **** DESIGN PARAMETERS FOR   R1')
      WRITE(3,40)DIAM
      WRITE(3,45)TOTHT
      WRITE(3,130)TOTCT
  130 FORMAT(1X,3X,' CATALYST (TONS)                        ='F6.0)
      WRITE(3,55)L
      WRITE(3,60)DROP
      WRITE(3,65)PRESS
C     DESIGN OF BURNER COOLER E-5
      AVGTI = (TEMPK(9) + TEMPK(10)) / 2.
      DENSI = 22. * PRES(5) / AVGTI
      PHI = ( (TEMPK(9) - TEMPK(10)) / (AVGTI - 478.)) * .782
      BI = 1.0 + .00184 / PHI
      CI = .570E - 10 * BI / DENSI * * 2
      CEI = .750E - 08
      QA = A * 60.
      DT = (AVGTI - TEMPK(38)) * 1.8
      U = 1.0
      ENR = 800.
      DO 135 MM=1,100
      U = U + .3
      AREA = QA / (U * DT)
      CA = (16000. * (AREA / 1000.) * * .88) / AREA * (ENR / 1000.)
      CAI = CA * .20 / 8300.
      RATIO = 1.0
      GIO = ( (CAI / (CEI * CI)) / (3.5 * RATIO - 1.)) * * .357
      HI = .555E - 02 * GIO * * .8
      REPV = 1. / HI
      V = 1. / REPV
      IF (ABS(U - V) - .5) 140,140,135
  135 CONTINUE
  140 FI = .055 * (.094 / ( (2.067 / 12.) * GIO)) * * .2
      PDP1 = (1.00248 * 4. * FI * 20. * GIO * * 2) / (2. * 4.17E + 08 *
     1DENSI * 2.067)
      WRITE(3,145)
  145 FORMAT(/////' **** DESIGN PARAMETERS FOR   E5')
      WRITE(3,90)QA
      WRITE(3,95)U
      WRITE(3,100)DT
      WRITE(3,105)AREA
      WRITE(3,60)PDP1
      WRITE(3,65)PRESS
      CALL LINK(N90)
      END
*STORE
```

SUBPROGRAM N 90 - EQUIPMENT DESIGN

STATEMENT NOS.	DESCRIPTION
160 / 800	E 2 Design
810 / 1500	T 2 Design
1510 / 1860	E 4 Design
1870 / 2240	E 6 Design
2250 / 2790	E 7 Design

N90 page1

```
      DEFINEFILE8(10,40,U,I8) ,9(1,40,U,I9) ,7(10,90,U,I7)
      DIMENSIONACIDM(45) ,H2OM(45) ,TOTM(45) ,SO2M(45) ,ZN2M(45) ,O2M(45
     1) ,TEMPK(45) ,SO3M(45) ,VAT(8) ,PRES(20) ,Y(90) ,Z(90)
      READ(9'1) SO3,SO2,O2,ZN2,TOT,TEMP,RH,RAT,U,A,PRESS,NJ,TT,QE,E,B,F,
     1C
      READ(7'1) (TEMPK(I) ,I = 1,45)
      READ(7'2) (H2OM(I) ,I = 1,45)
      READ(7'3) (TOTM(I) ,I = 1,45)
      READ(7'4) (SO2M(I) ,I = 1,45)
      READ(7'5) (ZN2M(I) ,I = 1,45)
      READ(7'6) (O2M(I) ,I = 1,45)
      READ(7'7) (ACIDM(I) ,I = 1,45)
      READ(7'8) (SO3M(I) ,I = 1,45)
      READ(8'9) (VAT(I) ,I = 1,8)
C     DESIGN OF REACTOR COOLER E-2
      DO 5 M=1,20
      PRES(M) = PRESS
    5 CONTINUE
      AVGTO = (TEMPK(14) + TEMPK(23)) / 2.
      AVGTI = (TEMPK(12) + TEMPK(13)) / 2.
      DENSO = 22. * PRES(8) / AVGTO
      DENSI = 22. * PRES(6) / AVGTI
      DELT1 = TEMPK(12) - TEMPK(14)
      DELT2 = TEMPK(23) - TEMPK(13)
      TLMDL = ( (DELT2 - DELT1) / ALOG(DELT2 / DELT1)) * 1.8
      PHI = ( (TEMPK(13) - TEMPK(12)) / (AVGTO - AVGTI)) * .731
      BI = 1.0 + .00184 / PHI
      CI = .554E - 10 * BI / DENSI * * 2
      CO = .958E - 09 / DENSO * * 2
      CEI = .750E - 08
      CEO = CEI
      QB = B * 60.
      FNR = 800.
      U = 1.0
      DO 20 MJ=1,100
      U = U + .3
      AREA = QB / (U * TLMDL)
      CA = 7.0 * (AREA / 1000.) * * ( - .6) * (ENR / 400.)
      CAI = CA * .20 / 8300.
      RATIO = .95
      DO 10 MJ=1,50
      RATIO = RATIO + .03
      GIO = ( (CAI / (CEI * CI)) / (2.5 + 2.76 * (1. / RATIO))) * * .357
      GOO = ( (CAI / (CEO * CO)) / (3.75 + 3.39 * RATIO)) * * .351
      HI = .529E - 02 * GIO * * .8
      HO = .72E - 01 * GOO * * .6
      RATIA = 1.14 * (HO / HI)
      IF (ABS(RATIA - RATIO) - .02) 15,15,10
   10 CONTINUE
   15 REPV = 1. / HI + .876 / HO
      V = 1. / REPV
      IF (ABS(U - V) - .5) 25,25,20
   20 CONTINUE
   25 FI = .055 * (.0772 / ( (2.067 / 12.) * GIO)) * * .2
      PDP1 = (BI * 4. * FI * 20. * GIO * * 2) / (2. * 4.17E + 08 * DENSI
     1 * 2.067)
      FO = .31 * (.082 / ( (2.375 / 12.) * GOO)) * * .15
      FO = .31 * (.082 / ( (2.375 / 12.) * GOO)) * * .15
      TMASS = TOTM(14) * 29. * 60.
      TUBE = TMASS / (GIO * .0234)
```

N90 page 2

```
      PDP2 = (4. * FO * 1. * TUBE * GOO * * 2) / (2. * 4.17E + 08 * DENS
     10)
      PDP2 = PDP1 * 1.75
      WRITE(3,30)
   30 FORMAT(/////' **** DESIGN PARAMETERS FOR   E2')
      WRITE(3,35)QB
   35 FORMAT(//4X,' HEAT EXCHANGE DUTY(BTU/HR)           ='E12.4)
      WRITE(3,40)U
   40 FORMAT(1X,3X,' HEAT TRANSFER COFF(BTU/SQ FT/DEG F)='F6.1)
      WRITE(3,45)TLMDL
   45 FORMAT(1X,3X,' TEMPERATURE DIFFERENCE(DEG F)       ='F6.0)
      WRITE(3,50)AREA
   50 FORMAT(1X,3X,' SURFACE AREA(SQ FT)                 ='F7.0)
      WRITE(3,55)PDP1
   55 FORMAT(1X,3X,' PRESSURE DROP INSIDE (PSI)          ='F5.1)
      WRITE(3,60)PDP2
   60 FORMAT(1X,3X,' PRESSURE DROP OUTSIDE(PSI)          ='F5.1)
      WRITE(3,65)PRESS
   65 FORMAT(1X,3X,' PRESSURE(ATM)                       ='F5.0)
C     DESIGN CALCULATIONS OF ABSORPTION COLUMN  T2
      G = (SO3M(13) * 80. + SO2M(13) * 64. + ZN2M(13) * 28. + O2M(13) *
     132.) / 60.
      TL = (RAT * 2.5 * 15.2) / 60.
      DENLL = 15.2 / .1337
      DENVV = 22. * PRES(7) / ( (TEMPK(13) + TEMPK(14)) / 2.)
      VISCL = 3.8
      COA = (TL / G) * (DENVV / DENLL) * * .5
      TM = .377E + 04 * COA + .754E + 03
      TN = .209E + 04 * COA + .880E + 03
      TLOAD = .50
      DELTP = 1.5 * TLOAD
      TO = DELTP / (TM * DELTP + TN)
      AREA = (G / DENLL) * (VISCL * * .2 / (DENVV * TO)) * * .5
      GO = G * 3600. / AREA
      COFJ = 1.06 * (.146 * GO / .0675) * * ( - .41)
      PENO = (.25 * .0675 / .027) * * .666
      HH = COFJ * .25 * GO / PENO
      TF13 = 1.8 * (TEMPK(13) - 273.) + 32.
      TF14 = 1.8 * (TEMPK(14) - 273.) + 32.
      TF16 = 1.8 * (TEMPK(16) - 273.) + 32.
      TF15 = 1.8 * (TEMPK(15) - 273.) + 32.
      TEMRO = (TF13 - TF14) / (TF16 - TF15)
      TINCR = (TF13 - TF14) / 50.
      TEMG = TF13
      TEML = TF16
      DO 70 LM=1,50
      TEMG1 = TEMG
      TEMG = TEMG - TINCR
      TAVG = (TEMG1 + TEMG) / 2.
      TEML1 = TEML
      TEML = TEML - TINCR * (1. / TEMRO)
      TAVL = (TEML1 + TEML) / 2.
      DIFF = TAVG - TAVL
      RECP = 1. / DIFF
      Y(LM) = RECP
   70 CONTINUE
      NDIM = 50
      H = TINCR
      CALL QSF(H,Y,Z,NDIM)
      NDIM = 50
      TINTR = Z(NDIM)
```

N90 page 3

```
      TM13 = (SO3M(13) * 80. + SO2M(13) * 64. + O2M(13) * 32. + ZN2M(13)
     1* 28.) * 60.
      TM14 = (SO3M(14) * 80. + SO2M(14) * 64. + O2M(14) * 32. + ZN2M(14)
     1* 28.) * 60.
      TMAVG = (TM13 + TM14) / 2.
      CP = .25
      SAREA = (TINTR * TMAVG * CP) / HH
      THIGH = SAREA / (28. * AREA)
      THIGH = 1.333 * THIGH
      DIAM = (AREA / .785) * * .5
      IF (THIGH - 10.) 75,75,80
   75 THIGH = DIAM
   80 PAC = AREA * THIGH
      BEDS = THIGH / (3. * DIAM)
      NBEDS = BEDS + 1
      PRED = (.75 * THIGH + .30 * (.75 * THIGH)) / 12. * (14.7 / 34.)
      THIGH = THIGH + .30 * DIAM
      WRITE(3,85)
   85 FORMAT(/////' **** DESIGN PARAMETERS FOR   T2')
      WRITE(3,90)DIAM
   90 FORMAT(//4X,' DIAMETER(FT)                          ='F5.0)
      WRITE(3,95)THIGH
   95 FORMAT(1X,3X,' HEIGHT OR LENGHT(FT)                 ='F5.0)
      WRITE(3,100)PAC
  100 FORMAT(1X,3X,' PACKING (CU FT)                      ='F6.0)
      WRITE(3,105)NBEDS
  105 FORMAT(1X,3X,' NUMBER OF BEDS                       ='I3)
      WRITE(3,55)PRED
      WRITE(3,65)PRESS
C     DESIGN OF WASTE HEAT BOILER   E-4
      AVGTI = (TEMPK(25) + TEMPK(26)) / 2.
      DENSI = 22. * PRES(12) / AVGTI
      PHI = ( (TEMPK(25) - TEMPK(26)) / (AVGTI - 478.)) * .782
      BI = 1.0 + .00184 / PHI
      CI = .580E - 10 * BI / DENSI * * 2
      CEI = .75E - 08
      QE = E * 60.
      ENR = 800.
      DTT = (AVGTI - TEMPK(32)) * 1.8
      U = 1.0
      DO 110 ML=1,200
      U = U + .3
      AREA = QE / (U * DTT)
      CA = (16000. * (AREA / 1000.) * * .88) / AREA * (ENR / 1000.)
      CAI = CA * .20 / 3300.
      RATIO = 1.0
      GIO = ( (CAI / (CEI * CI)) / (3.5 * RATIO - 1.)) * * .357
      HI = .530E - 02 * GIO * * .8
      REPV = 1. / HI
      V = 1. / REPV
      ARE = QE / (V * DTT)
      IF (ABS(U - V) - .5) 115,115,110
  110 CONTINUE
  115 FI = .055 * (.084 / ( (2.067 / 12.) * GIO)) * * .2
      PDP1 = (BI * 4. * FI * 20. * GIO * * 2) / (2. * 4.17E + 08 * DENSI
     1 * 2.067)
      WRITE(3,120)
  120 FORMAT(/////' **** DESIGN PARAMETERS FOR   E4')
      WRITE(3,35)QE
      WRITE(3,40)U
      WRITE(3,45)DTT
```

N90 page 4

```
      WRITE(3,50)AREA
      WRITE(3,55)PDP1
      WRITE(3,65)PRESS
C     DESIGN OF FEED WATER HEATER E6
      AVGTI = (TEMPK(26) + TEMPK(27)) / 2.
      DENSI = 22. * PRES(13) / AVGTI
      PHI = (TEMPK(26) - TEMPK(27)) / 230. * 1.8 * .780
      BI = 1.0 + .00184 / PHI
      CI = 7.1E - 11 / DENSI * * 2
      CEI = .75E - 08
      FQ = F * 60.
      DT = 840.
      U = 1.0
      ENR = 800.
      DO 125 NN=1,100
      U = U + .3
      AREA = FQ / (U * DT)
      CA = (16000. * (AREA / 1000.) * * .88) / AREA * (ENR / 1000.)
      CAI = CA * .20 / 8300.
      RATIO = 1.0
      GIO = ( (CAI / (CEI * CI)) / (3.5 * RATIO - 1.0)) * * .357
      HI = .55E - 02 * GIO * * .8
      HO = 150.
      REPV = 1. / HI + .876 / HO
      V = 1. / REPV
      ARE = FQ / (V * 840.)
      IF (ABS(U - V) - .5) 130,130,125
  125 CONTINUE
  130 FI = .055 * (.0635 / ( (1.033 / 12.) * GIO)) * * .2
      PDP1 = (BI * 4. * FI * 20. * GIO * * 2) / (2. * 4.17E + 08 * DENSI
     1 * 1.033)
      PDP2 = 3.0
      WRITE(3,135)
  135 FORMAT(/////' **** DESIGN PARAMETERS FOR   E6')
      WRITE(3,35)FQ
      WRITE(3,40)U
      WRITE(3,45)DT
      WRITE(3,50)AREA
      WRITE(3,55)PDP1
      WRITE(3,60)PDP2
      WRITE(3,65)PRESS
C     DESIGN OF ECONOMIZER E7
      AVGTO = (TEMPK(23) + TEMPK(24)) / 2.
      AVGTI = (TEMPK(37) + TEMPK(7)) / 2.
      DENSO = 22. * PRES(9) / AVGTO
      DENSI = 22. * PRES(3) / AVGTI
      DELT1 = TEMPK(7) - TEMPK(24)
      DELT2 = TEMPK(37) - TEMPK(23)
      TLMDL = ( (DELT2 - DELT1) / ALOG(DELT2 / DELT1)) * 1.8
      PHI = ( (TEMPK(37) - TEMPK(7)) / (AVGTI - AVGTO)) * .782
      BI = 1.0 + .00184 / PHI
      CI = .570E - 10 * BI / DENSI * * 2
      CO = .100E - 08 / DENSO * * 2
      CEI = .750E - 08
      CEO = CEI
      QC = C * 60.
      ENR = 800.
      U = 1.0
      DO 150 JM=1,100
      U = U + .3
      AREA = QC / (U * TLMDL)
```

N90 page 5

```
      CA = 7.0 * (AREA / 1000.) * * ( - .6) * (ENR / 400.)
      CAI = CA * .20 / 8300.
      RATIO = .95
      DO 140 MJ=1,25
      RATIO = RATIO + .01
      GIO = ( (CAI / (CEI * CI)) / (2.5 + 2.76 * (1. / RATIO))) * * .357
      GOO = ( (CAI / (CEO * CO)) / (3.75 + 3.39 * RATIO)) * * .351
      HI = .525E - 02 * GIO * * .8
      HO = .7E - 01 * GOO * * .6
      RATIA = 1.14 * (HO / HI)
      IF (ABS(RATIA - RATIO) - .020) 145,145,140
  140 CONTINUE
  145 REPV = 1. / HI + .876 / HO
      V = 1. / REPV
      IF (ABS(U - V) - .5) 155,155,150
  150 CONTINUE
  155 FI = .055 * (.0772 / ( (2.067 / 12.) * GIO)) * * .2
      PDP1 = (BI * 4. * FI * 20. * GIO * * 2) / (2. * 4.17E + 08 * DENSI
     1 * 2.067)
      FO = .31 * (.082 / ( (2.375 / 12.) * GOO)) * * .15
      TMASS = TOTM(23) * 29. * 60.
      TUBE = TMASS / (GIO * .0234)
      PDP2 = (4. * FO * 1. * TUBE * GOO * * 2) / (2. * 4.17E + 08 * DENS
     10)
      PDP2 = 2.1 * PDP1
      WRITE(3,160)
  160 FORMAT(/////' **** DESIGN PARAMETERS FOR    E7')
      WRITE(3,35)QC
      WRITE(3,40)U
      WRITE(3,45)TLMDL
      WRITE(3,50)AREA
      WRITE(3,55)PDP1
      WRITE(3,60)PDP2
      WRITE(3,65)PRESS
      END
*STORE
```

APPENDIX C - MISCELLANEOUS INFORMATION

1) "The Effect of Pressure on Equilibrium Conversion"

2) Total catalyst requirement vs pressure

FIG. (1)

EQUILIBRIUM CONVERSION VS TEMPERATURE

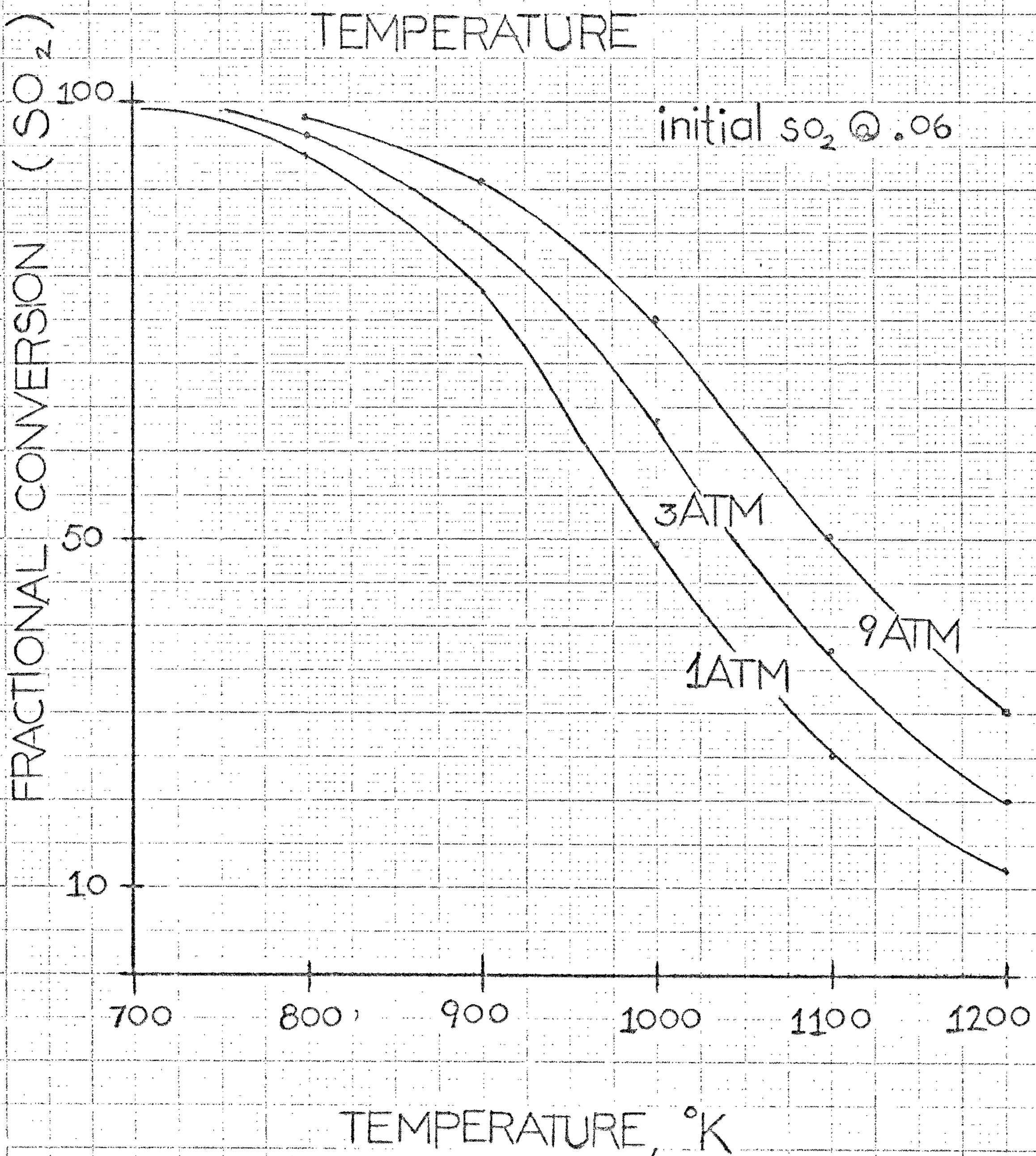
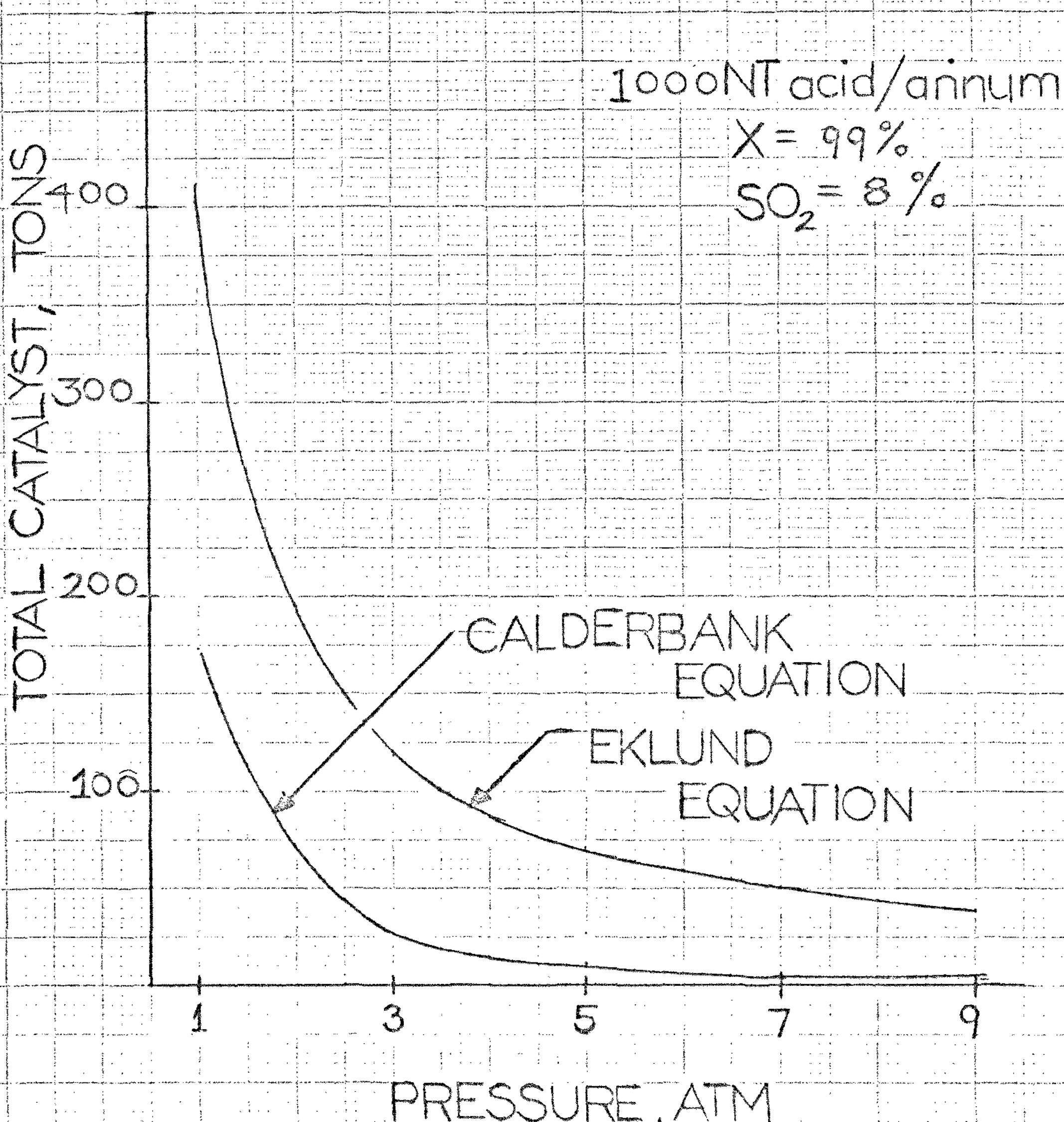


FIG (2)
TOTAL CATALYST
VS
PRESSURE



APPENDIX D - COMPUTER OUTPUT

**** DESIGN PARAMETERS FOR F1

FILTER CAPACITY(ACFM)	=	79310.
PRESSURE(ATM)	=	1.

**** DESIGN PARAMETERS FOR T1

DIAMETER(FT)	=	16.5
HEIGHT OR LENGHT(FT)	=	21.4
PACKING (CU FT)	=	3538.
NUMBER OF BEDS	=	1
PRESSURE DROP INSIDE (PSI)	=	0.5
PRESSURE(ATM)	=	1.

**** DESIGN PARAMETERS FOR G1

DIAMETER(FT)	=	22.2
HEIGHT OR LENGHT(FT)	=	33.4
PRESSURE DROP INSIDE (PSI)	=	0.5
PRESSURE(ATM)	=	1.

**** DESIGN PARAMETERS FOR E1

HEAT EXCHANGE DUTY(BTU/HR)	=	0.3856E 08
HEAT TRANSFER COFF(BTU/SQ FT/DEG F)	=	8.4
TEMPERATURE DIFFERENCE(DEG F)	=	648.
SURFACE AREA(SQ FT)	=	7001.
PRESSURE DROP INSIDE (PSI)	=	1.3
PRESSURE(ATM)	=	1.

**** DESIGN PARAMETERS FOR F2

```
DIAMETER(FT)                            =  10.8
HEIGHT OR LENGHT(FT)                    =  10.8
PRESSURE DROP INSIDE (PSI)              =  0.3
PRESSURE(ATM)                           =   1.
```

**** DESIGN PARAMETERS FOR R1

```
DIAMETER(FT)                            =  29.2
HEIGHT OR LENGHT(FT)                    =  52.8
CATALYST (TONS)                         =  473.
NUMBER OF BEDS                          =  3
PRESSURE DROP INSIDE (PSI)              =  3.5
PRESSURE(ATM)                           =   1.
```

**** DESIGN PARAMETERS FOR E5

```
HEAT EXCHANGE DUTY(BTU/HR)              = 0.8789E 07
HEAT TRANSFER COFF(BTU/SQ FT/DEG F)=  9.0
TEMPERATURE DIFFERENCE(DEG F)           =  533.
SURFACE AREA(SQ FT)                     =  1811.
PRESSURE DROP INSIDE (PSI)              =  1.5
PRESSURE(ATM)                           =   1.
```

**** DESIGN PARAMETERS FOR E2

```
HEAT EXCHANGE DUTY(BTU/HR)              =  0.3091E 08
HEAT TRANSFER COFF(BTU/SQ FT/DEG F)=  2.5
TEMPERATURE DIFFERENCE(DEG F)           =  298.
SURFACE AREA(SQ FT)                     = 41479.
PRESSURE DROP INSIDE (PSI)              =  0.2
PRESSURE DROP OUTSIDE(PSI)              =  0.5
PRESSURE(ATM)                           =   1.
```

**** DESIGN PARAMETERS FOR I2

```
DIAMETER(FT)                              =  18.
HEIGHT OR LENGHT(FT)                      =  23.
PACKING (CU FT)                           = 4580.
NUMBER OF BEDS                            =  1
PRESSURE DROP INSIDE (PSI)                =  0.6
PRESSURE(ATM)                             =  1.

**** DESIGN PARAMETERS FOR    E4

HEAT EXCHANGE DUTY(BTU/HR)                =  0.4603E 08
HEAT TRANSFER COFF(BTU/SQ FT/DEG F)=  8.7
TEMPERATURE DIFFERENCE(DEG F)             =  330.
SURFACE AREA(SQ FT)                       = 15838.
PRESSURE DROP INSIDE (PSI)                =  1.3
PRESSURE(ATM)                             =  1.

**** DESIGN PARAMETERS FOR    E6

HEAT EXCHANGE DUTY(BTU/HR)                =  0.1666E 08
HEAT TRANSFER COFF(BTU/SQ FT/DEG F)=  10.8
TEMPERATURE DIFFERENCE(DEG F)             =  840.
SURFACE AREA(SQ FT)                       =  1819.
PRESSURE DROP INSIDE (PSI)                =  3.3
PRESSURE DROP OUTSIDE(PSI)                =  3.0
PRESSURE(ATM)                             =  1.

**** DESIGN PARAMETERS FOR    E7

HEAT EXCHANGE DUTY(BTU/HR)                =  0.3524E 08
HEAT TRANSFER COFF(BTU/SQ FT/DEG F)=  1.9
TEMPERATURE DIFFERENCE(DEG F)             =  560.
SURFACE AREA(SQ FT)                       = 33120.
PRESSURE DROP INSIDE (PSI)                =  0.2
PRESSURE DROP OUTSIDE(PSI)                =  0.5
PRESSURE(ATM)                             =  1.
```

**** DESIGN PARAMETERS FOR F1

FILTER CAPACITY(ACFM)	=	25669.
PRESSURE(ATM)	=	3.

**** DESIGN PARAMETERS FOR T1

DIAMETER(FT)	=	13.1
HEIGHT OR LENGHT(FT)	=	17.0
PACKING (CU FT)	=	1772.
NUMBER OF BEDS	=	1
PRESSURE DROP INSIDE (PSI)	=	0.4
PRESSURE(ATM)	=	3.

**** DESIGN PARAMETERS FOR G1

DIAMETER(FT)	=	15.4
HEIGHT OR LENGHT(FT)	=	23.1
PRESSURE DROP INSIDE (PSI)	=	0.5
PRESSURE(ATM)	=	3.

**** DESIGN PARAMETERS FOR E1

HEAT EXCHANGE DUTY(BTU/HR)	=	0.3856E 08
HEAT TRANSFER COFF(BTU/SQ FT/DEG F)	=	16.2
TEMPERATURE DIFFERENCE(DEG F)	=	648.
SURFACE AREA(SQ FT)	=	3650.
PRESSURE DROP INSIDE (PSI)	=	1.9
PRESSURE(ATM)	=	3.

**** DESIGN PARAMETERS FOR F2

```
DIAMETER(FT)                               =   6.4
HEIGHT OR LENGHT(FT)                       =   6.4
PRESSURE DROP INSIDE (PSI)                 =  0.3
PRESSURE(ATM)                              =   3.
```

**** DESIGN PARAMETERS FOR R1

```
DIAMETER(FT)                               =  22.1
HEIGHT OR LENGHT(FT)                       =  31.3
CATALYST (TONS)                            =  139.
NUMBER OF BEDS                             =  3
PRESSURE DROP INSIDE (PSI)                 =  1.7
PRESSURE(ATM)                              =   3.
```

**** DESIGN PARAMETERS FOR E5

```
HEAT EXCHANGE DUTY(BTU/HR)                 =  0.7003E 07
HEAT TRANSFER COFF(BTU/SQ FT/DEG F)=  18.0
TEMPERATURE DIFFERENCE(DEG F)              =  543.
SURFACE AREA(SQ FT)                        =   712.
PRESSURE DROP INSIDE (PSI)                 =  2.2
PRESSURE(ATM)                              =   3.
```

**** DESIGN PARAMETERS FOR E2

```
HEAT EXCHANGE DUTY(BTU/HR)                 =  0.2964E 08
HEAT TRANSFER COFF(BTU/SQ FT/DEG F)=   5.1
TEMPERATURE DIFFERENCE(DEG F)              =  293.
SURFACE AREA(SQ FT)                        = 19399.
PRESSURE DROP INSIDE (PSI)                 =  0.5
PRESSURE DROP OUTSIDE(PSI)                 =  0.8
PRESSURE(ATM)                              =   3.
```

**** DESIGN PARAMETERS FOR T2

```
DIAMETER(FT)                              =  14.
HEIGHT OR LENGHT(FT)                      =  18.
PACKING (CU FT)                           = 2247.
NUMBER OF BEDS                            =  1
PRESSURE DROP INSIDE (PSI)                =  0.4
PRESSURE(ATM)                             =  3.


**** DESIGN PARAMETERS FOR    E4

HEAT EXCHANGE DUTY(BTU/HR)                =  0.4444E 08
HEAT TRANSFER COFF(BTU/SQ FT/DEG F)=  17.4
TEMPERATURE DIFFERENCE(DEG F)             =  330.
SURFACE AREA(SQ FT)                       =  7689.
PRESSURE DROP INSIDE (PSI)                =  1.8
PRESSURE(ATM)                             =  3.


**** DESIGN PARAMETERS FOR    E6

HEAT EXCHANGE DUTY(BTU/HR)                =  0.1609E 08
HEAT TRANSFER COFF(BTU/SQ FT/DEG F)=  20.1
TEMPERATURE DIFFERENCE(DEG F)             =  840.
SURFACE AREA(SQ FT)                       =  948.
PRESSURE DROP INSIDE (PSI)                =  4.7
PRESSURE DROP OUTSIDE(PSI)                =  3.0
PRESSURE(ATM)                             =  3.


**** DESIGN PARAMETERS FOR    E7

HEAT EXCHANGE DUTY(BTU/HR)                =  0.3435E 08
HEAT TRANSFER COFF(BTU/SQ FT/DEG F)=   3.9
TEMPERATURE DIFFERENCE(DEG F)             =  561.
SURFACE AREA(SQ FT)                       = 15297.
PRESSURE DROP INSIDE (PSI)                =  0.4
PRESSURE DROP OUTSIDE(PSI)                =  0.9
PRESSURE(ATM)                             =  3.
```

```
****  DESIGN PARAMETERS FOR   F1

        FILTER CAPACITY(ACFM)                        = 13597.
        PRESSURE(ATM)                                =   5.


****  DESIGN PARAMETERS FOR   T1

        DIAMETER(FT)                                 =  11.4
        HEIGHT OR LENGHT(FT)                         =  14.8
        PACKING (CU FT)                              = 1164.
        NUMBER OF BEDS                               =   1
        PRESSURE DROP INSIDE (PSI)                   =   0.4
        PRESSURE(ATM)                                =   5.


****  DESIGN PARAMETERS FOR   G1

        DIAMETER(FT)                                 =  13.0
        HEIGHT OR LENGHT(FT)                         =  19.5
        PRESSURE DROP INSIDE (PSI)                   =   0.5
        PRESSURE(ATM)                                =   5.


****  DESIGN PARAMETERS FOR   E1

        HEAT EXCHANGE DUTY(BTU/HR)                   =  0.3856E 08
        HEAT TRANSFER COFE(BTU/SQ FT/DEG F)          =  22.2
        TEMPERATURE DIFFERENCE(DEG F)                =  648.
        SURFACE AREA(SQ FT)                          =  2668.
        PRESSURE DROP INSIDE (PSI)                   =  2.3
        PRESSURE(ATM)                                =   5.
```

**** DESIGN PARAMETERS FOR F2

DIAMETER(FT)	=	5.0
HEIGHT OR LENGHT(FT)	=	5.0
PRESSURE DROP INSIDE (PSI)	=	0.3
PRESSURE(ATM)	=	5.

**** DESIGN PARAMETERS FOR R1

DIAMETER(FT)	=	19.5
HEIGHT OR LENGHT(FT)	=	22.6
CATALYST (TONS)	=	83.
NUMBER OF BEDS	=	2
PRESSURE DROP INSIDE (PSI)	=	1.1
PRESSURE(ATM)	=	5.

**** DESIGN PARAMETERS FOR E5

HEAT EXCHANGE DUTY(BTU/HR)	=	0.3782E 08
HEAT TRANSFER COFF(BTU/SQ FT/DEG F)	=	23.1
TEMPERATURE DIFFERENCE(DEG F)	=	548.
SURFACE AREA(SQ FT)	=	2973.
PRESSURE DROP INSIDE (PSI)	=	2.3
PRESSURE(ATM)	=	5.

**** DESIGN PARAMETERS FOR E2

HEAT EXCHANGE DUTY(BTU/HR)	=	0.3356E 08
HEAT TRANSFER COFF(BTU/SQ FT/DEG F)	=	7.2
TEMPERATURE DIFFERENCE(DEG F)	=	387.
SURFACE AREA(SQ FT)	=	11861.
PRESSURE DROP INSIDE (PSI)	=	0.6
PRESSURE DROP OUTSIDE(PSI)	=	1.2
PRESSURE(ATM)	=	5.

**** DESIGN PARAMETERS FOR T2

DIAMETER(FT)	=	12.
HEIGHT OR LENGHT(FT)	=	16.
PACKING (CU FT)	=	1528.
NUMBER OF BEDS	=	1
PRESSURE DROP INSIDE (PSI)	=	0.4
PRESSURE(ATM)	=	5.

**** DESIGN PARAMETERS FOR E4

HEAT EXCHANGE DUTY(BTU/HR)	=	0.4027E 08
HEAT TRANSFER COFF(BTU/SQ FT/DEG F)	=	23.7
TEMPERATURE DIFFERENCE(DEG F)	=	330.
SURFACE AREA(SQ FT)	=	5123.
PRESSURE DROP INSIDE (PSI)	=	2.2
PRESSURE(ATM)	=	5.

**** DESIGN PARAMETERS FOR E6

HEAT EXCHANGE DUTY(BTU/HR)	=	0.1456E 08
HEAT TRANSFER COFF(BTU/SQ FT/DEG F)	=	26.1
TEMPERATURE DIFFERENCE(DEG F)	=	840.
SURFACE AREA(SQ FT)	=	661.
PRESSURE DROP INSIDE (PSI)	=	5.6
PRESSURE DROP OUTSIDE(PSI)	=	3.0
PRESSURE(ATM)	=	5.

**** DESIGN PARAMETERS FOR E7

HEAT EXCHANGE DUTY(BTU/HR)	=	0.2469E 08
HEAT TRANSFER COFF(BTU/SQ FT/DEG F)	=	5.7
TEMPERATURE DIFFERENCE(DEG F)	=	532.
SURFACE AREA(SQ FT)	=	8002.
PRESSURE DROP INSIDE (PSI)	=	0.6
PRESSURE DROP OUTSIDE(PSI)	=	1.4
PRESSURE(ATM)	=	5.

**** DESIGN PARAMETERS FOR E1

FILTER CAPACITY(ACFM)	=	9712.
PRESSURE(ATM)	=	7.

**** DESIGN PARAMETERS FOR T1

DIAMETER(FT)	=	10.7
HEIGHT OR LENGHT(FT)	=	13.9
PACKING (CU FT)	=	974.
NUMBER OF BEDS	=	1
PRESSURE DROP INSIDE (PSI)	=	0.3
PRESSURE(ATM)	=	7.

**** DESIGN PARAMETERS FOR G1

DIAMETER(FT)	=	11.6
HEIGHT OR LENGHT(FT)	=	17.4
PRESSURE DROP INSIDE (PSI)	=	0.5
PRESSURE(ATM)	=	7.

**** DESIGN PARAMETERS FOR E1

HEAT EXCHANGE DUTY(BTU/HR)	=	0.3856E 08
HEAT TRANSFER COFF(BTU/SQ FT/DEG F)	=	27.3
TEMPERATURE DIFFERENCE(DEG F)	=	648.
SURFACE AREA(SQ FT)	=	2171.
PRESSURE DROP INSIDE (PSI)	=	2.5
PRESSURE(ATM)	=	7.

**** DESIGN PARAMETERS FOR F2

DIAMETER(FT)	=	4.3
HEIGHT OR LENGHT(FT)	=	4.3
PRESSURE DROP INSIDE (PSI)	=	0.3
PRESSURE(ATM)	=	7.

**** DESIGN PARAMETERS FOR R1

DIAMETER(FT)	=	17.9
HEIGHT OR LENGHT(FT)	=	19.7
CATALYST (TONS)	=	59.
NUMBER OF BEDS	=	2
PRESSURE DROP INSIDE (PSI)	=	0.9
PRESSURE(ATM)	=	7.

**** DESIGN PARAMETERS FOR E5

HEAT EXCHANGE DUTY(BTU/HR)	=	0.3817E 08
HEAT TRANSFER COFF(BTU/SQ FT/DEG F)	=	28.2
TEMPERATURE DIFFERENCE(DEG F)	=	549.
SURFACE AREA(SQ FT)	=	2452.
PRESSURE DROP INSIDE (PSI)	=	2.6
PRESSURE(ATM)	=	7.

**** DESIGN PARAMETERS FOR E2

HEAT EXCHANGE DUTY(BTU/HR)	=	0.3319E 08
HEAT TRANSFER COFF(BTU/SQ FT/DEG F)	=	9.0
TEMPERATURE DIFFERENCE(DEG F)	=	382.
SURFACE AREA(SQ FT)	=	9536.
PRESSURE DROP INSIDE (PSI)	=	0.8
PRESSURE DROP OUTSIDE(PSI)	=	1.4
PRESSURE(ATM)	=	7.

**** DESIGN PARAMETERS FOR T2

```
DIAMETER(FT)                              =  11.
HEIGHT OR LENGHT(FT)                      =  15.
PACKING (CU FT)                           = 1269.
NUMBER OF BEDS                            =  1
PRESSURE DROP INSIDE (PSI)                =  0.4
PRESSURE(ATM)                             =  7.
```

**** DESIGN PARAMETERS FOR E4

```
HEAT EXCHANGE DUTY(BTU/HR)                =  0.4027E 08
HEAT TRANSFER COFF(BTU/SQ FT/DEG F)=  29.1
TEMPERATURE DIFFERENCE(DEG F)             =  330.
SURFACE AREA(SQ FT)                       =  4176.
PRESSURE DROP INSIDE (PSI)                =  2.5
PRESSURE(ATM)                             =  7.
```

**** DESIGN PARAMETERS FOR E6

```
HEAT EXCHANGE DUTY(BTU/HR)                =  0.1456E 08
HEAT TRANSFER COFF(BTU/SQ FT/DEG F)=  30.9
TEMPERATURE DIFFERENCE(DEG F)             =  840.
SURFACE AREA(SQ FT)                       =  559.
PRESSURE DROP INSIDE (PSI)                =  6.3
PRESSURE DROP OUTSIDE(PSI)                =  3.0
PRESSURE(ATM)                             =  7.
```

**** DESIGN PARAMETERS FOR E7

```
HEAT EXCHANGE DUTY(BTU/HR)                =  0.2507E 08
HEAT TRANSFER COFF(BTU/SQ FT/DEG F)=   7.2
TEMPERATURE DIFFERENCE(DEG F)             =  533.
SURFACE AREA(SQ FT)                       =  6434.
PRESSURE DROP INSIDE (PSI)                =  0.8
PRESSURE DROP OUTSIDE(PSI)                =  1.7
PRESSURE(ATM)                             =  7.
```

```
**** DESIGN PARAMETERS FOR   F1

          FILTER CAPACITY(ACFM)                      =  7554.
          PRESSURE(ATM)                              =  9.


**** DESIGN PARAMETERS FOR   T1

          DIAMETER(FT)                               =  10.2
          HEIGHT OR LENGHT(FT)                       =  13.3
          PACKING (CU FT)                            =  856.
          NUMBER OF BEDS                             =  1
          PRESSURE DROP INSIDE (PSI)                 =  0.3
          PRESSURE(ATM)                              =  9.


**** DESIGN PARAMETERS FOR   G1

          DIAMETER(FT)                               =  10.7
          HEIGHT OR LENGHT(FT)                       =  16.0
          PRESSURE DROP INSIDE (PSI)                 =  0.5
          PRESSURE(ATM)                              =  9.


**** DESIGN PARAMETERS FOR   E1

          HEAT EXCHANGE DUTY(BTU/HR)                 =  0.3856E 08
          HEAT TRANSFER COFE(BTU/SQ FT/DEG F)        =  30.9
          TEMPERATURE DIFFERENCE(DEG F)              =  648.
          SURFACE AREA(SQ FT)                        =  1919.
          PRESSURE DROP INSIDE (PSI)                 =  2.7
          PRESSURE(ATM)                              =  9.
```

**** DESIGN PARAMETERS FOR F2

```
DIAMETER(FT)                             =   3.8
HEIGHT OR LENGHT(FT)                     =   3.8
PRESSURE DROP INSIDE (PSI)               =  0.3
PRESSURE(ATM)                            =   9.
```

**** DESIGN PARAMETERS FOR R1

```
DIAMETER(FT)                             =  16.8
HEIGHT OR LENGHT(FT)                     =  17.9
CATALYST (TONS)                          =   46.
NUMBER OF BEDS                           =  2
PRESSURE DROP INSIDE (PSI)               =  0.8
PRESSURE(ATM)                            =   9.
```

**** DESIGN PARAMETERS FOR E5

```
HEAT EXCHANGE DUTY(BTU/HR)               =  0.3852E 08
HEAT TRANSFER COFF(BTU/SQ FT/DEG F)      =  30.9
TEMPERATURE DIFFERENCE(DEG F)            =  551.
SURFACE AREA(SQ FT)                      =  2252.
PRESSURE DROP INSIDE (PSI)               =  2.8
PRESSURE(ATM)                            =   9.
```

**** DESIGN PARAMETERS FOR E2

```
HEAT EXCHANGE DUTY(BTU/HR)               =  0.3281E 08
HEAT TRANSFER COFF(BTU/SQ FT/DEG F)      =  10.5
TEMPERATURE DIFFERENCE(DEG F)            =  377.
SURFACE AREA(SQ FT)                      =  8206.
PRESSURE DROP INSIDE (PSI)               =  0.9
PRESSURE DROP OUTSIDE(PSI)               =  1.5
PRESSURE(ATM)                            =   9.
```

**** DESIGN PARAMETERS FOR T2

```
DIAMETER(FT)                              =  11.
HEIGHT OR LENGHT(FT)                      =  14.
PACKING (CU FT)                           = 1109.
NUMBER OF BEDS                            =  1
PRESSURE DROP INSIDE (PSI)                =  0.3
PRESSURE(ATM)                             =   9.
```

**** DESIGN PARAMETERS FOR E4

```
HEAT EXCHANGE DUTY(BTU/HR)                =  0.4027E 08
HEAT TRANSFER COFF(BTU/SQ FT/DEG F)=  33.6
TEMPERATURE DIFFERENCE(DEG F)             =  330.
SURFACE AREA(SQ FT)                       =  3618.
PRESSURE DROP INSIDE (PSI)                =  2.7
PRESSURE(ATM)                             =   9.
```

**** DESIGN PARAMETERS FOR E6

```
HEAT EXCHANGE DUTY(BTU/HR)                =  0.1456E 08
HEAT TRANSFER COFF(BTU/SQ FT/DEG F)=  30.9
TEMPERATURE DIFFERENCE(DEG F)             =  840.
SURFACE AREA(SQ FT)                       =   559.
PRESSURE DROP INSIDE (PSI)                =  6.7
PRESSURE DROP OUTSIDE(PSI)                =  3.0
PRESSURE(ATM)                             =   9.
```

**** DESIGN PARAMETERS FOR E7

```
HEAT EXCHANGE DUTY(BTU/HR)                =  0.2544E 08
HEAT TRANSFER COFF(BTU/SQ FT/DEG F)=   8.4
TEMPERATURE DIFFERENCE(DEG F)             =  535.
SURFACE AREA(SQ FT)                       =  5590.
PRESSURE DROP INSIDE (PSI)                =  0.9
PRESSURE DROP OUTSIDE(PSI)                =  1.9
PRESSURE(ATM)                             =   9.
```

**** DESIGN PARAMETERS FOR F1

```
FILTER CAPACITY(ACFM)                        =  5229.
PRESSURE(ATM)                                =  13.
```

**** DESIGN PARAMETERS FOR I1

```
DIAMETER(FT)                                 =   9.6
HEIGHT OR LENGHT(FT)                         =  12.5
PACKING (CU FT)                              =  712.
NUMBER OF BEDS                               =  1
PRESSURE DROP INSIDE (PSI)                   =  0.3
PRESSURE(ATM)                                =  13.
```

**** DESIGN PARAMETERS FOR G1

```
DIAMETER(FT)                                 =   9.4
HEIGHT OR LENGHT(FT)                         =  14.2
PRESSURE DROP INSIDE (PSI)                   =  0.5
PRESSURE(ATM)                                =  13.
```

**** DESIGN PARAMETERS FOR E1

```
HEAT EXCHANGE DUTY(BTU/HR)                   =  0.3856E 08
HEAT TRANSFER COFE(BTU/SQ FT/DEG F)          =  30.9
TEMPERATURE DIFFERENCE(DEG F)                =  648.
SURFACE AREA(SQ FT)                          =  1919.
PRESSURE DROP INSIDE (PSI)                   =  3.1
PRESSURE(ATM)                                =  13.
```

**** DESIGN PARAMETERS FOR F2

```
DIAMETER(FT)                                  =  3.2
HEIGHT OR LENGHT(FT)                          =  3.2
PRESSURE DROP INSIDE (PSI)                    =  0.3
PRESSURE(ATM)                                 =  13.
```

**** DESIGN PARAMETERS FOR R1

```
DIAMETER(FT)                                  =  15.3
HEIGHT OR LENGHT(FT)                          =  15.4
CATALYST (TONS)                               =  31.
NUMBER OF BEDS                                =  2
PRESSURE DROP INSIDE (PSI)                    =  0.6
PRESSURE(ATM)                                 =  13.
```

**** DESIGN PARAMETERS FOR E5

```
HEAT EXCHANGE DUTY(BTU/HR)                    =  0.3922E 08
HEAT TRANSFER COFF(BTU/SQ FT/DEG F)=  30.9
TEMPERATURE DIFFERENCE(DEG F)                 =  554.
SURFACE AREA(SQ FT)                           =  2280.
PRESSURE DROP INSIDE (PSI)                    =  3.1
PRESSURE(ATM)                                 =  13.
```

**** DESIGN PARAMETERS FOR E2

```
HEAT EXCHANGE DUTY(BTU/HR)                    =  0.3206E 08
HEAT TRANSFER COFF(BTU/SQ FT/DEG F)=  12.9
TEMPERATURE DIFFERENCE(DEG F)                 =  366.
SURFACE AREA(SQ FT)                           =  6726.
PRESSURE DROP INSIDE (PSI)                    =  1.4
PRESSURE DROP OUTSIDE(PSI)                    =  2.4
PRESSURE(ATM)                                 =  13.
```

**** DESIGN PARAMETERS FOR I2

```
DIAMETER(FT)                                  =  10.
HEIGHT OR LENGHT(FT)                          =  13.
PACKING (CU FT)                               =  915.
NUMBER OF BEDS                                =  1
PRESSURE DROP INSIDE (PSI)                    =  0.3
PRESSURE(ATM)                                 =  13.
```

```
**** DESIGN PARAMETERS FOR    E4

HEAT EXCHANGE DUTY(BTU/HR)                    =  0.4027E 08
HEAT TRANSFER COFF(BTU/SQ FT/DEG F)=  42.0
TEMPERATURE DIFFERENCE(DEG F)                 =  330.
SURFACE AREA(SQ FT)                           =  2896.
PRESSURE DROP INSIDE (PSI)                    =  3.1
PRESSURE(ATM)                                 =  13.
```

```
**** DESIGN PARAMETERS FOR    E6

HEAT EXCHANGE DUTY(BTU/HR)                    =  0.1456E 08
HEAT TRANSFER COFF(BTU/SQ FT/DEG F)=  30.9
TEMPERATURE DIEFERENCE(DEG F)                 =  840.
SURFACE AREA(SQ FT)                           =   559.
PRESSURE DROP INSIDE (PSI)                    =  7.5
PRESSURE DROP OUTSIDE(PSI)                    =  3.0
PRESSURE(ATM)                                 =  13.
```

```
**** DESIGN PARAMETERS FOR    E7

HEAT EXCHANGE DUTY(BTU/HR)                    =  0.2619E 08
HEAT TRANSFER COFF(BTU/SQ FT/DEG F)=  10.5
TEMPERATURE DIFFERENCE(DEG F)                 =  538.
SURFACE AREA(SQ FT)                           =  4585.
PRESSURE DROP INSIDE (PSI)                    =  1.0
PRESSURE DROP OUTSIDE(PSI)                    =  2.2
PRESSURE(ATM)                                 =  13.
```

APPENDIX E - PHYSICAL PROPERTIES

PHYSICAL PROPERTIES

Temperature °F	Cp, Btu/# F				μ, #/ft-hr.			K, Btu / hr. Ft^2 (°F/Ft.)	
	Air	SO_3	SO_2	98% H_2SO_4	Air	SO_2	98% Acid	Air	SO_2
100				.35			26.4	.0181	.0069
200	.2412	.161	.141	.37	.0521	.00039	8.2		
300				.38					
400	.2446	.174	.161	.40	.0630	.00049		.0225	.0075
500									
600	.2502	.185	.168		.0726	.00059		.0266	.0080
800	.2566	.194	.172		.0813	.00070		.0303	.0085
1000	.2630	.201	.176		.0892	.00081		.0337	.0088
1200	.2687	.204	.18		.0967	.00090		.0369	.0090