ENERGY CONSERVATION IN COAL CONVERSION

Using Second Law Analysis to Pinpoint Inefficiencies in Coal Conversion Processes

E. J. Mueller
L. Fucich

Carnegie-Mellon University
Pittsburgh, PA 15213

August, 1978

Prepared for

THE U.S. DEPARTMENT OF ENERGY
Pittsburgh Energy Technology Center
UNDER CONTRACT NO. EY77S024196

ABSTRACT

This study performs a second law analysis on the Fischer-Tropsch complex proposed by the Ralph M. Parsons Company. The second law efficiency of each process unit making up the complex was computed in order to determine areas where process improvements could be made.

The complex as a whole has a first law efficiency of 70% and a second law efficiency of 68.7%. Two areas where efficiencies could be improved are: unit 14, acid gas removal with a second law efficiency of 80.2%, and unit 21, sulfur recovery, which has a second law efficiency of 66.4%. Other areas had efficiencies greater than 87% which indicates energy recovery and conservation techniques had been implemented in the design of the complex.

ACKNOWLEDGEMENT

I would like to thank T. Ruppel of The Pittsburgh Energy Technology Center for his contributions to this study.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

Purpose

This report performs a second law analysis on the Fischer-Tropsch Complex of the Ralph M. Parson Company. A second law analysis, based on the concept of availability, is used to pinpoint and evaluate the dissipations in the F-T complex, and also to determine the efficiency of the complex. The analysis is performed on the entire complex to determine an over-all efficiency, and also on the individual process units to reveal areas for improvement. A second law analysis is used instead of a first law (energy) analysis because the results are measured with availability or useful energy and thus are the true efficiencies.

Second Law Analysis

Second Law Analysis is based on the concept of availability sometimes referred to as useful energy, potential energy, exergy and other names. This concept can seem abstract and difficult to understand but availability can be considered as the measure of a material to cause a desired change. Therefore, any material which is not in equilibrium with its surroundings has the potential of doing useful work as it approaches equilibrium with its surroundings, and this is the definition of availability.[1,12]

Description of Fischer-Tropsch Complex

The Ralph M. Parsons Fischer-Tropsch Complex is a coal conversion facility designed to use high-sulfur coal and convert it to SNG (substitute natural gas), LPGs (liquified petroleum gases), light and heavy naphthas, diesel fuel, fuel oil, oxygenates (primarily alcohols), and electrical power for in-plant use and export. Using the Fischer-Tropsch process, the coal is gasified, the gases purified, and reacted to produce the above products. The industrial complex consists of a large mine that produces 40,000 tons per day (TPD) of run-of-mine coal which is supplied to a coal preparation plant, which in turn supplies 30,000 TPD of clean, sized coal with a heating value of 12,550 Btu/lb to the Fischer-Tropsch plant. All electricity and steam required for the Fischer-Tropsch complex are generated within the plant; therefore, the input to the plant is coal, air, and water. The overall material balance is shown on Figure 1 and the energy balance is shown on Figure 2. The estimated fixed capital investment is $1.5 billion based on fourth quarter 1975 dollars.

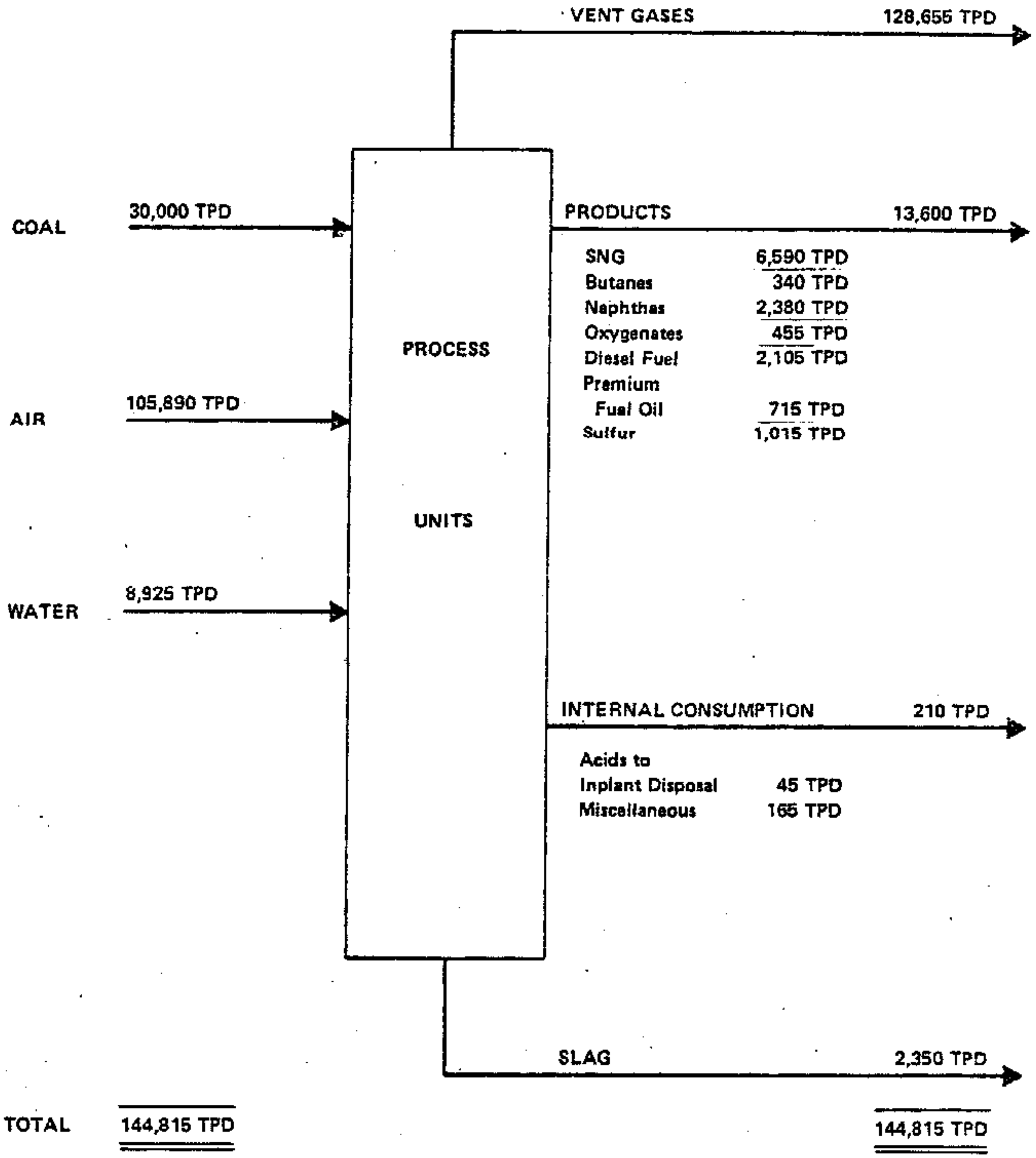


FIGURE 1

Overall Material Balance

548<

Reproduced from R&D Report No. 114 -
Interim Report No. 3 by the
Ralph M. Parsons Company.

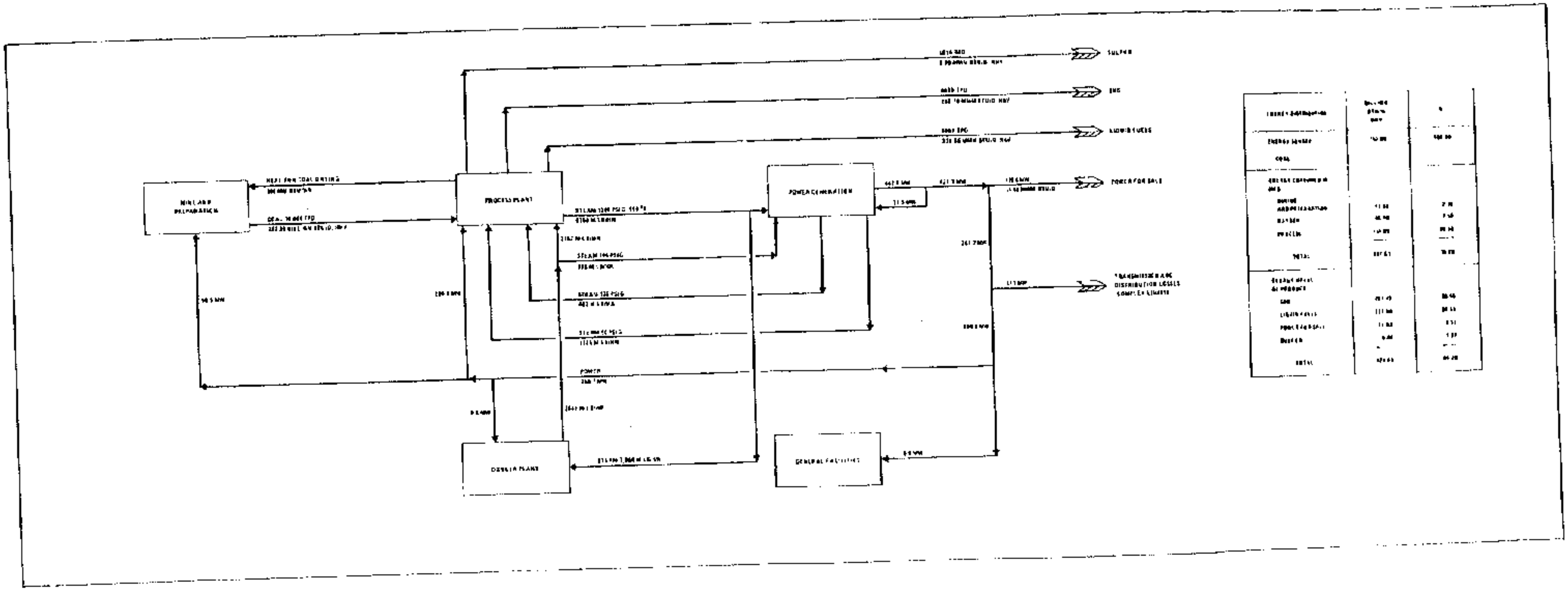


FIGURE 2

Energy Balance

Reproduced from R&D Report No. 114 - Interim Report No. 3
by the Ralph M. Parsons Company.

Procedure for Calculating Second Law Efficiencies

A second law analysis of the Parsons Fischer-Tropsch Complex was performed by first considering the entire plant, its inputs and outputs and then considering each separate process unit in order to pinpoint the process units which were the most energy inefficient.

The basis of the second law analysis is the concept of available energy or availability. Availabilities were calculated using equation (1)

$$(1)\quad A = \overset{\circ}{m}\,[((Cp\ (T-To)) + Hc + Hv) - To\ ((Cp\ \ell n\ (\frac{T}{To})) + \frac{Hv}{To} - \frac{R}{M}\ In\ (\frac{P}{Po}) + S°comb)\ \frac{RTo}{M} - \ell n\ Xo]$$

A = availability, Btu/HR
$\dot{m}$ = mass flow of the stream, lb_m/HR
Cp = constant pressure specific heat of the stream, Btu/lb_m-°R
T = temperature of the stream °R
To = dead state temperature = 537°F = 77°F
Hc = heat of combustion of the stream, Btu/lb_m
HV = heat of vaporization of the stream, Btu/lb_m
R = universal gas constant 1545 $\frac{ft\text{-}lb_f}{lb_m\text{-}°R}$
M = molecular weight
P = pressure of the stream, psia
Po = dead state pressure 14.7 psia
$S°comb$ = entropy of combustion, Btu/lb_m-°R
Xo = mole fraction of substance in stream that occurs in nature.

Once the availabilities of all the inlet and outlet streams were determined, the second law efficiency was found as shown in equation 2:

(2) $E_{2L} = \frac{\Sigma Ao}{\Sigma Ai}$ (9)

E_{2L} = second law efficiency

Ao = availability out of unit

Ai = availability into unit

The availability loss through the unit is expressed as the sum of the availabilities in minus the sum of the availabilities out; this loss, then, is a measure of the inreversibility of the process.(7)

Using the relationships presented above, the second law efficiencies and the availability losses through the entire complex and each separate process unit were found and are shown on Tables 1 and 2 along with availabilities in and out.

Some examples of availability calculations follow.

The availability of coal was not determined using equation (1) but was determined from an equation presented in reference 12:

$$a_{coal} = hc_{coal} \times \frac{a_{carbon}}{hc_{carbon}}$$

a_{coal} = availability of coal $\frac{Btu}{lb_m}$

hc_{coal} = heat of combustion of coal, Btu/lb

a_{carbon} = availability of carbon, Btu/lb

hc_{carbon} = heat of combustion of carbon, 14,067 Btu/lb.

Therefore,

$$a_{coal} = 12{,}550 \frac{Btu}{lb} \times \frac{14760}{14067}$$

or,

$$a_{coal} = 13{,}168 \text{ Btu/lb}$$

The availability of steam was calculated using a simplified version of equation (1):

$$a_{steam} = ((h_{t,p} - h_{to,po})) - To\ (S_{t,p} - S_{to,po}))$$

Using the steam tables for steam at 510 psia and 670°F:

$$a_{steam} = ((1340-49.5) - 537(1.592-.093))\ \frac{Btu}{lb_m}$$

$$a_{steam} = 485.5\ \frac{Btu}{lb_m}$$

Where,

$h_{t,p}$ = enthalpy of steam at pressure P and temperature T

$h_{to,po}$ = enthalpy of steam at pressure Po and temperature To

$S_{t,p}$ = entropy of steam at pressure P and temperature T

$S_{to,po}$ = entropy of steam at pressure Po and temperature To

An availability using equation 1 is shown here for an oxygen - nitrogen stream:

Oxygen	Nitrogen	
24,947 mph	509 mph	
449,046 lb/hr	14252 lb/hr	$\dot{m}$
.245 $\frac{Btu}{lb°R}$	.258 $\frac{Btu}{lb°R}$	Cp
650°	650°	T
485 psia	485 psia	P
.2035	.7567	Xo

mph = moles per hour

$$A_{N2} = 14{,}252\ [((.258\ (650-77)) - 537\ (.258\ \mathrm{In}(\frac{1110}{537})) - (\frac{1545}{778}(28.01)\,\mathrm{In}(\frac{485}{14.7}))) - (\frac{1545\ (537)}{778\ (28.01)}\ \mathrm{In}(.7567)))]$$

$$A_{N2} = 2.72 \times 10^{6}\ \frac{Btu}{hr}$$

$$A_{02} = 449046 \left[((.245\ (650-77)) - 537\ ((.245\ \mathrm{In}(\frac{1110}{537})) - (\frac{1545}{778}(32)\ \mathrm{In}\ (\frac{485}{14.7}))) - (\frac{1545\ (537)}{778\ (32)}\ \mathrm{In}(.2035)))\right]$$

$$A_{02} = 96.3 \times 10^6\ \mathrm{Btu/hr}$$

$$A_{02N2} = A_{02} + A_{N2} = 2.72 \times 10^6\ \frac{\mathrm{Btu}}{\mathrm{hr}} + 96.3 \times 10^6\ \frac{\mathrm{Btu}}{\mathrm{hr}}$$

$$A_{02N2} = 99 \times 10^6\ \frac{\mathrm{Btu}}{\mathrm{hr}}$$

Availabilities for flows in and out of various process units are shown in Figure 3.

TABLE I

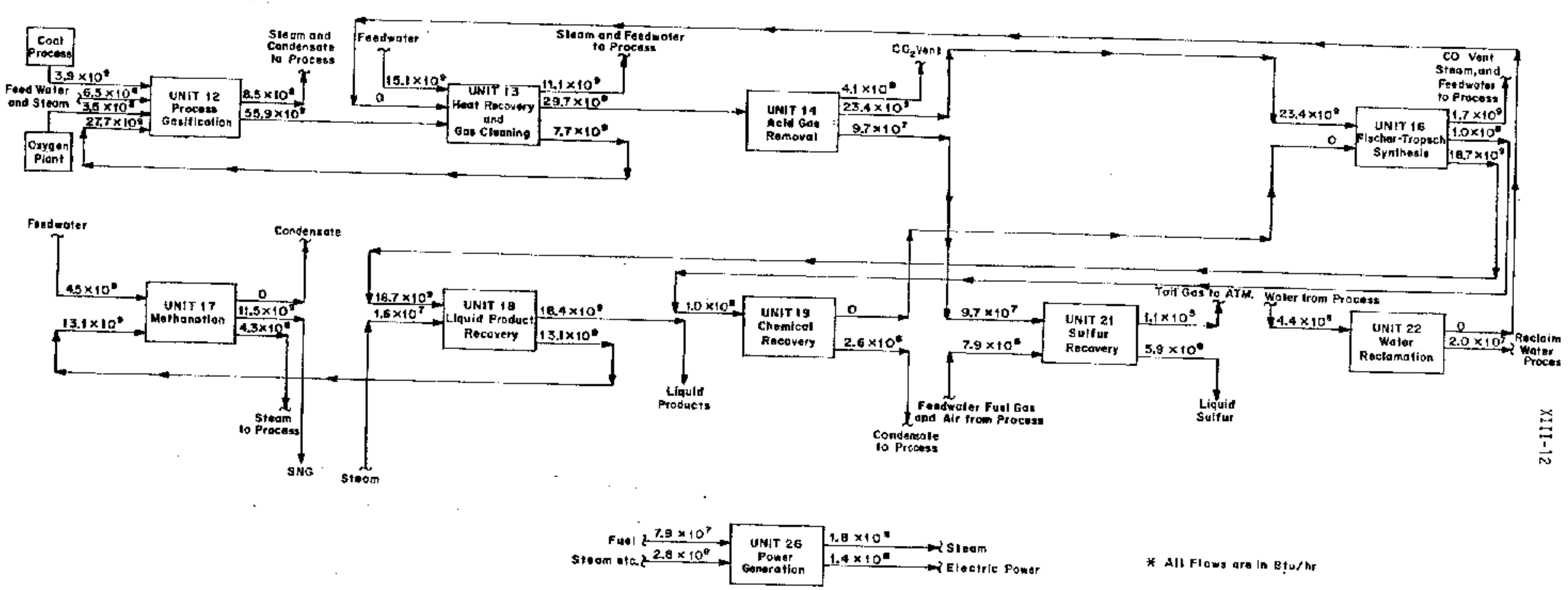
Overall Availabilities of the Fischer-Tropsch Complex Inlet and Outlet Streams

Inlet Streams

Stream Name	A, Availability, Btu/day	$\dot{m}$, Flow Rate, TPD
1. Coal Feed	790.09×10^9	30,000
2. Water	0	105,890
3. Air	0	8,925
Total	790.09×10^9	144,815

Outlet Streams

Stream Name	A, Availability, $\frac{\mathrm{Btu}}{\mathrm{day}}$	$\dot{m}$, Flow Rate, TPD
1. SNG	289.51×10^9	6,590
2. Oxygenates (Alcohols)	11.71×10^9	455
3. Diesel Fuel	83.83×10^9	2,105
4. Sulfur	9.13×10^9	1,015



* All Flows are in Btu/hr

FIGURE 3

AVAILABLE ENERGY FLOW DIAGRAM OF FISCHER-TROPSCH COMPLEX

Outlet Streams (cont)

Stream Name	A, Availability, $\frac{\text{Btu}}{\text{day}}$	$\dot{m}$, Flow Rate, TPD
5. Naphthas	94.93×10^9	2,380
6. Fuel Oil	27.87×10^9	715
7. LPG (Butanes)	14.24×10^9	340
8. Electricity	11.43×10^9	--
TOTAL	542.64×10^9	13,600

$$\varepsilon = \text{second law efficiency} = \frac{\text{Outlet Availability}}{\text{Inlet Availability}} = \frac{542.64 \times 10^9}{790.09 \times 10^9} = 68.7\%$$

Net Availability Loss = $A_{\text{inlet}} - A_{\text{outlet}}$ =

$$790.09 \times 10^9 - 542.64 \times 10^9 = 247.45 \times 10^9 \text{ Btu/day}$$

TABLE 2

Availabilities of Inlet and Outlet Streams, Net Availability Loss, and the Second Law Efficiency of Each Process Unit

Unit #	Inlet Availability, A_i, Btu/hr	Outlet Availability, A_o, Btu/hr	$A_i - A_o$	2nd Law Efficiency E, A_o/A_i
12	61.64×10^9	56.73×10^9	4.91×10^9	.920
13	70.83×10^9	68.58×10^9	2.25×10^9	.968
14	29.74×10^9	23.86×10^9	5.88×10^9	.802
16	23.50×10^9	20.54×10^9	2.96×10^9	.874
17	13.57×10^9	11.97×10^9	1.60×10^9	.882
18	18.74×10^9	29.50×10^9		
19	26.96×10^7	25.61×10^7	1.35×10^7	.950
21	88.45×10^7	58.73×10^7	29.72×10^7	.664
22	44.37×10^7	2.01×10^7	42.36×10^7	.045
26	3.64×10^9	1.96×10^9	1.68×10^9	.538

Conclusions:

The Fischer-Tropsch Complex with a first law or energy efficiency of 70% for the overall has a second law of 68.7%. Individual process unit second law efficiencies are listed in Table 2. From this table, Units 12 and 13 have the highest efficiencies, 92% and 96.8% respectively; therefore, there is little improvement to be made in these units. The power generation system, Unit 26, has a second law efficiency of 53.7%; however, this unit consists only of a turbine and generator and uses steam generated in Units 16 and 17. The second law analysis also pinpointed process units with low second law efficiencies thus revealing areas for possible improvement. Unit 14, Acid Gas Removal, which uses a Selexol solution process, has a second law efficiency of 80.2%. Perhaps the present Selexol Acid Gas Removal System can be replaced by a DEA system to become more efficient. A study such as Section IX, Alternate Acid Gas Removals System Study, of this report can be performed on the Acid Gas Removal Unit of the Fischer-Tropsch Complex. Sulfur Recovery, Unit 21, with a second law efficiency of 66.4%, is another area where possible improvements should be analyzed to achiever higher efficiencies. Unit 22, Water Reclamation, has an extremely low second law efficiency of 4.5% which seems to suggest an area for large improvements. This is misleading due to the fact that most of the outlet streams consist of water at ambient temperatures and pressures resulting in a low outlet availability.

As demonstrated in this study, a second law analysis is a very useful method by which to evaluate industrial plants and processes in order to pinpoint areas for improvement. The methodology used on the Fischer-Tropsch Complex can be applied to other industrial plants and processes.

REFERENCES

1. R.A. Gaggioli and P.J. Petit, "Second Law Analysis for Pinpointing the True Inefficiencies in Fuel Conversion Systems", Marquette University, 1975.

2. J. Yoon, "Design of Thermal Energy Systems by Employing Availability Concepts", M.S. Thesis, Marquette University, 1974.

3. T.C. Ruppel,W.C.Peters,and D.L. Schwartz,"The Role of Thermodynami Effectiveness in Evaluating Coal Conversion RD&D,Pergamon Press,N. 1977

4. "Fischer-Tropsch Complex Conceptual Design/Economic Analysis", R&D Report No. 114-Interim Report No. 3, The Ralph M. Parsons Company, January, 1973.

5. Conversation with R.A. Gaggiolo, Marquette University, Milwaukee, Wisconsin.

6. Conversation with T.C. Ruppel, Pittsburgh Energy Technology Center, Pittsburgh, Pennsylvania.

7. J. Coull and E.B. Stuart, "Equilibrium Thermodynamics", John Wiley and Sons, Inc., New York, 1964.

8. Keenan and Kayes, "Gas Tables", John Wiley and Sons, Inc., New York, 1948.

9. Van Wylen and Sonntagg, "Fundamentals of Classical Thermodynamics", John Wiley and Sons, Inc., New York, 1973.

10. ASHRAE, "Thermodynamic Properties of Refrigerants", New York, 1969.

11. D.R. Stull and N. Prophet, "JANAF Thermochemical Tables", Second Edition, Washington, D.C., 1971.

12. R.A. Gaggioli, J. Yoon, S.A. Patulski, A.J. Latus, and E.F. Obert, "Pinpointing the Real Inefficiencies in Power Plants and Energy Systems", April, 1975.

13. T. Baumeister and L.S. Marks, "Standard Handbook for Mechanical Engineers", Seventh Edition, McGraw-Hill Book Company, 1967.

14. G.R. Fryling, "Combustion Engineering", Revised Edition, Combustion Engineering, Inc., New York, 1966.