



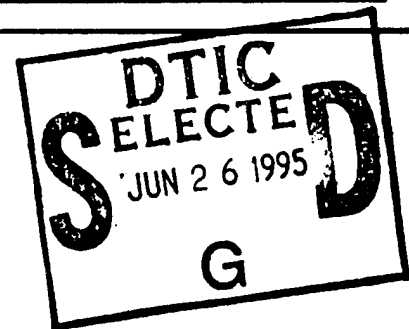
EW-3-82

June 1982

GAS TURBINE COMPARISONS  
USING THE EXERGY METHODS

by

V. J. LOPARDO  
Professor  
Mechanical Engineering Department



UNITED STATES NAVAL ACADEMY  
DIVISION OF  
ENGINEERING AND WEAPONS  
ANNAPOLIS, MARYLAND

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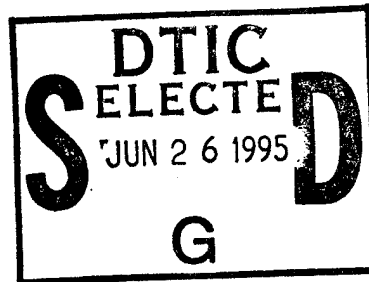
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## ABSTRACT

Using the exergetic methods of the Second Law of Thermodynamics several gas turbine configurations are compared and evaluated. In all cases the primary loss of exergy is associated with the combustion process and the exhaust stream. The use of a regenerator reduces the overall exergy dissipation.

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The objective of this study was to evaluate and compare the exergy flows for four different gas turbine configurations.

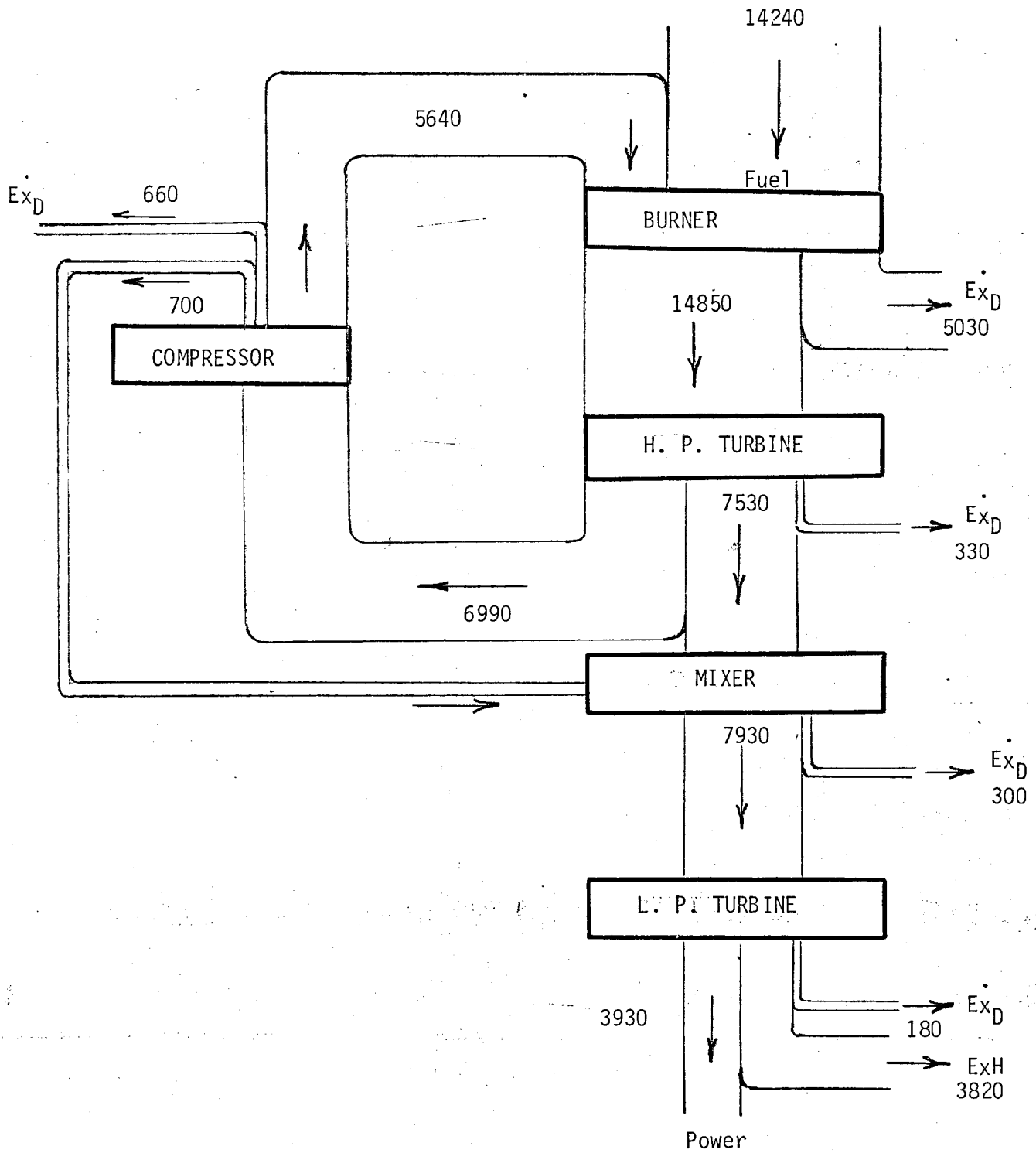
### Method

The gas turbines investigated were: GTF990, GTF990 WR<sub>86</sub>, GTF40WR<sub>86</sub> and GTF40WR<sub>96</sub>. The letters WR refer to "with regenerator" and the subscript is the regenerator effectiveness in percent. There were two approaches used in this study. The first was to assume that the fuel was C<sub>10</sub> H<sub>22</sub> and to compute the enthalpies and entropies at each station using the JANAF tables. This method yields information of the actual exergy flow at each station and was used for GTF990 and GTF990WR<sub>86</sub>. It is a more rigorous or detailed approach with all exergy values referenced to the same datum. The second method used the calculator program (see Report EW-9-81) for obtaining the properties in combination with the given lower heating value of the fuel. This method was used to determine the actual exergy losses or dissipation for all four turbines since the only known data were the LHV and the fuel air ratios. For a detailed description of the method see Report EW-2-82.

In both approaches the exergy was evaluated as  $[(h - T_0 S) - (h_0 - T_0 S_0)]$  with the exergy of kinetic and potential effects neglected.

### Results

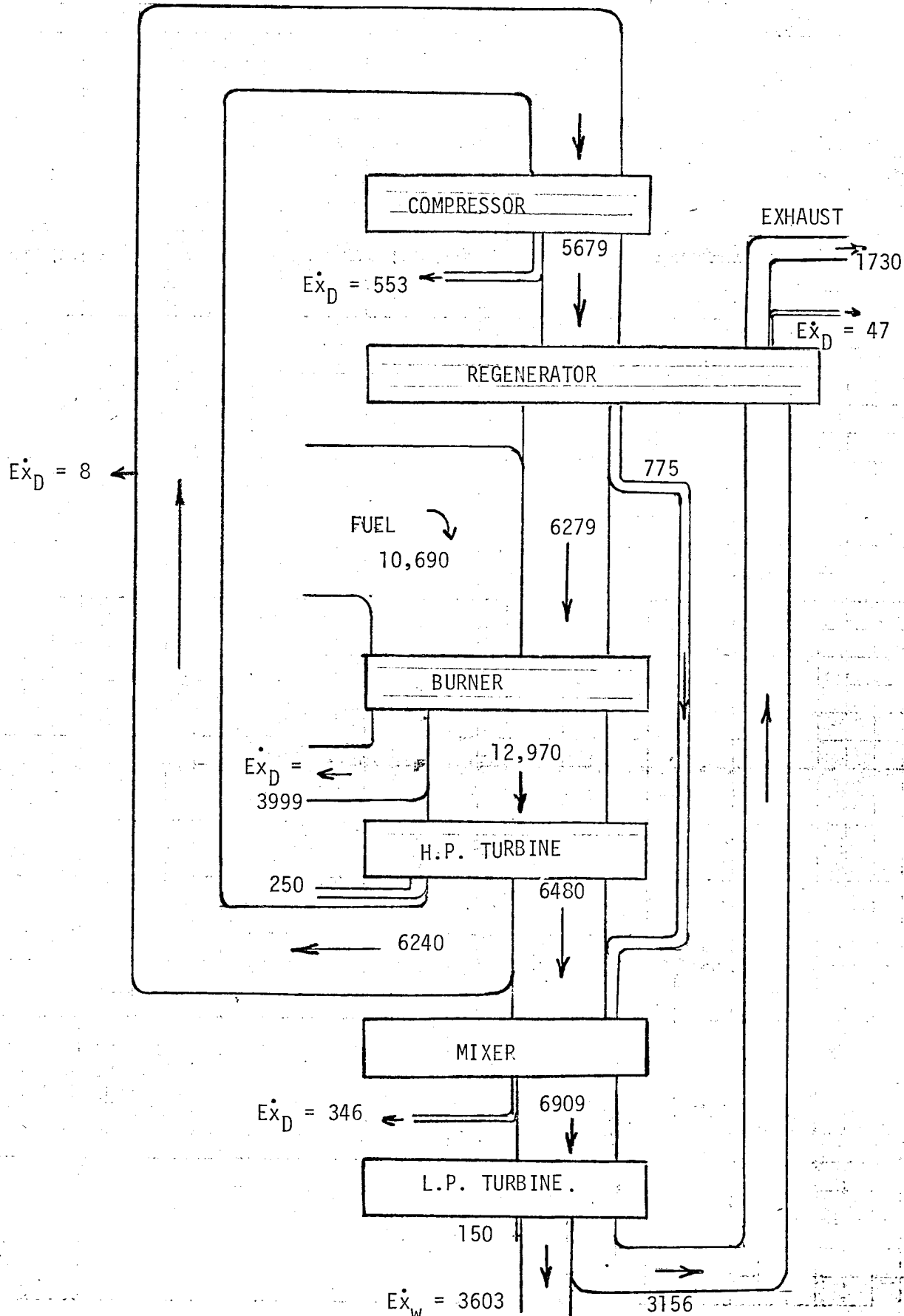
Figures 1 thru 5 summarize the results of this study. Figures 1 and 2 show the exergy flows in turbines GTF990 and GTF990WR<sub>86</sub> using dodecane (C<sub>10</sub>H<sub>22</sub>) as the fuel. Figure 3 compares the exergy dissipation for turbines GTF990WR<sub>86</sub> and GTF40WR<sub>86</sub>. Figures 4 and 5 give the losses for turbines GTF40WR<sub>96</sub> and GTF990 respectively.



EXERGY FLOW GTF990  
(All Units BTU/S)

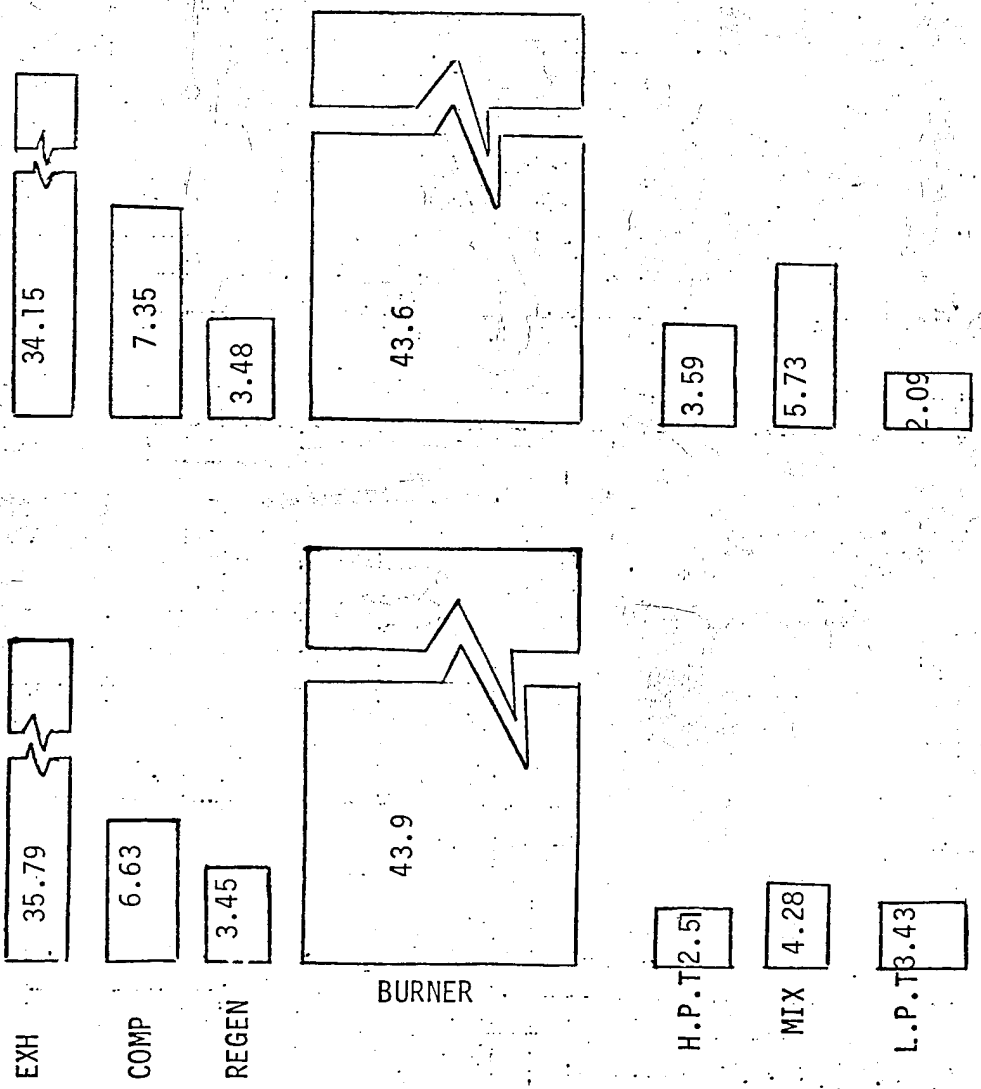
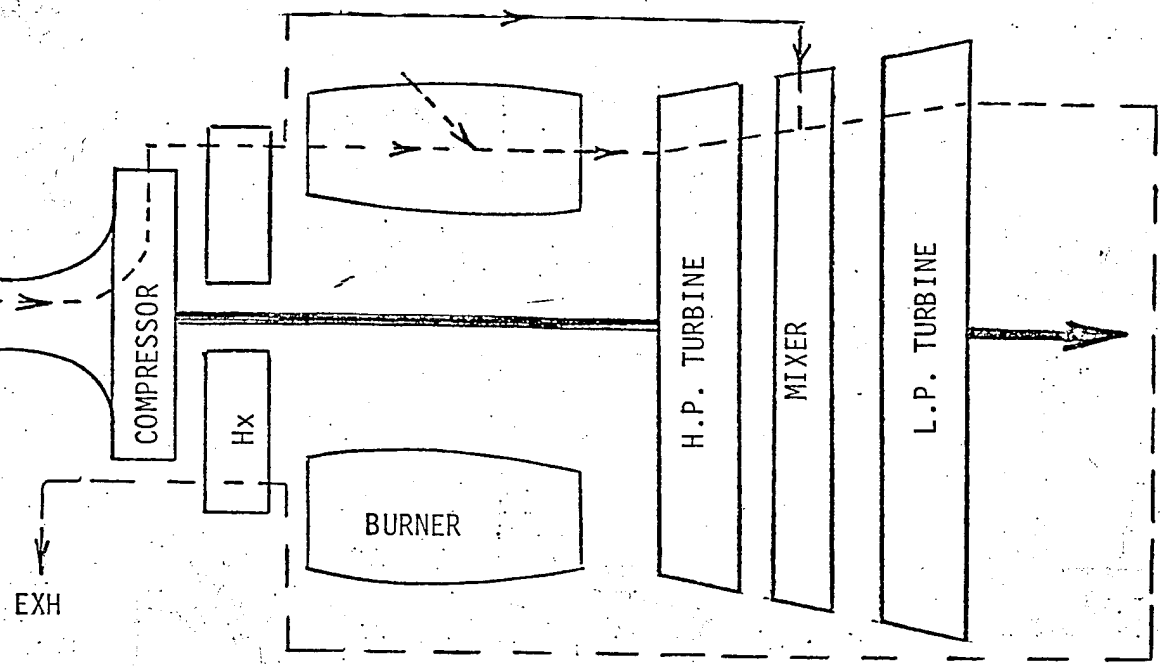
Fig. 1.

EXERGY FLOW DIAGRAM  
(All values in Btu/s)



$\dot{Ex}_W = 3603$   
Fig. 2

42389 200 SHEETS 3 SQUARE NATIONAL



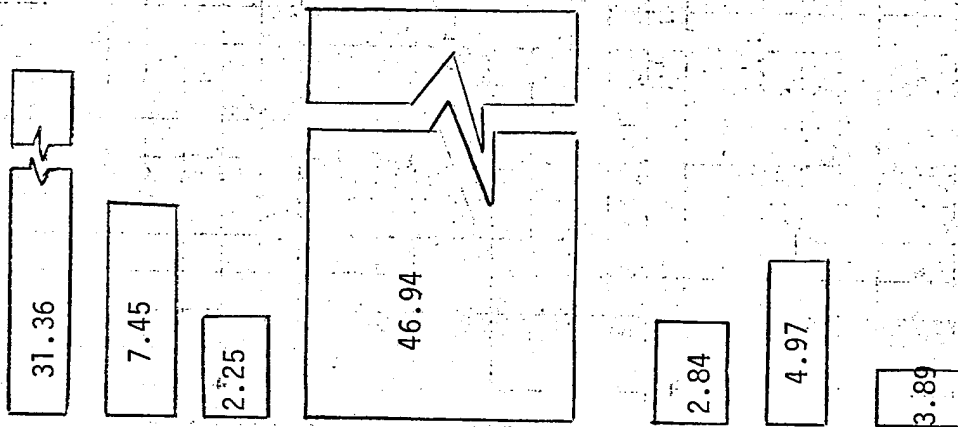
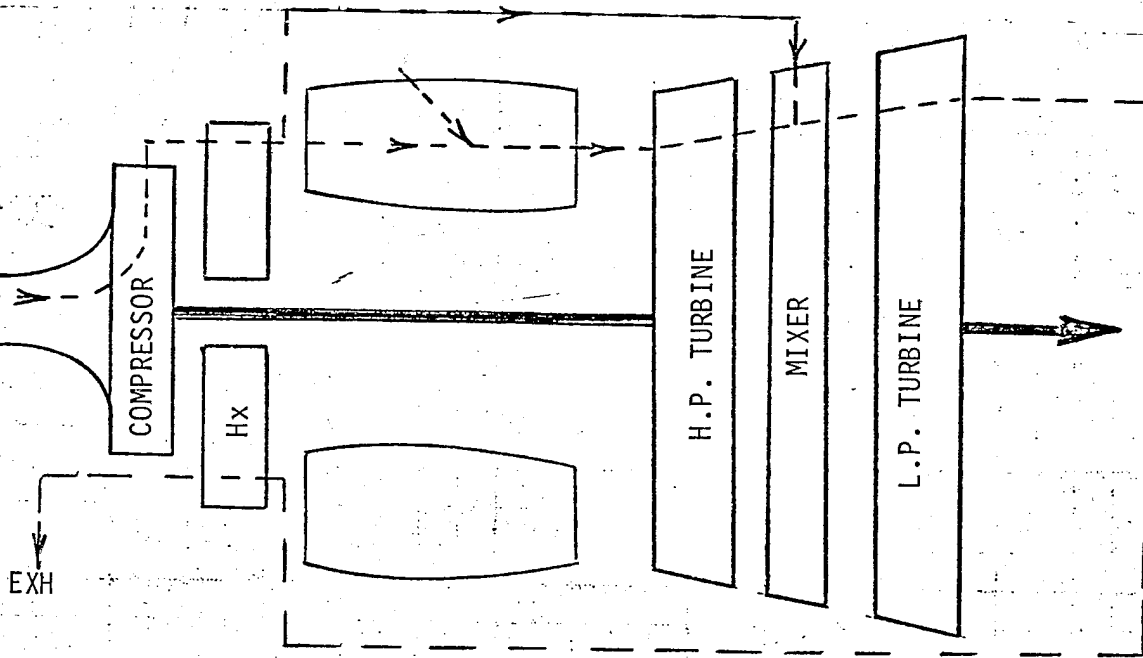
ALL numbers are in percentage

GTF990WR<sub>86</sub>

GTF40WR<sub>86</sub>

COMPARISON OF EXERGY DISSIPATION FOR GTF990WR<sub>86</sub> and GTF40WR<sub>86</sub>

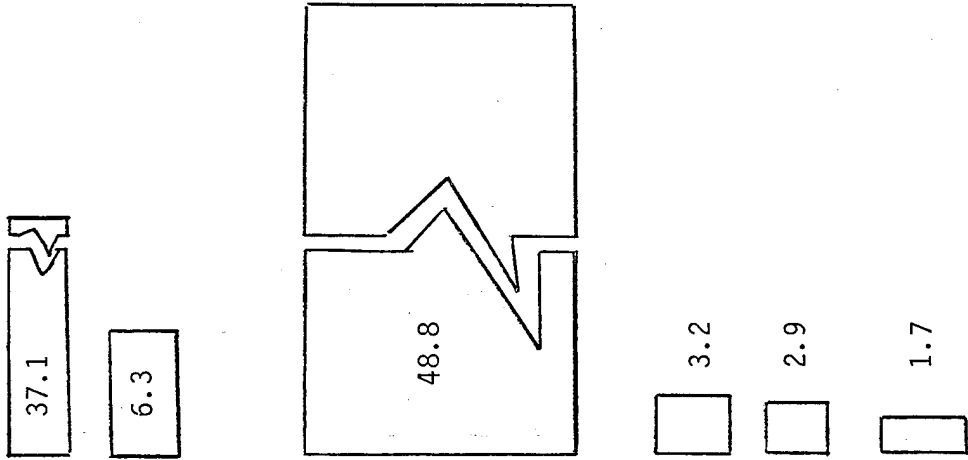
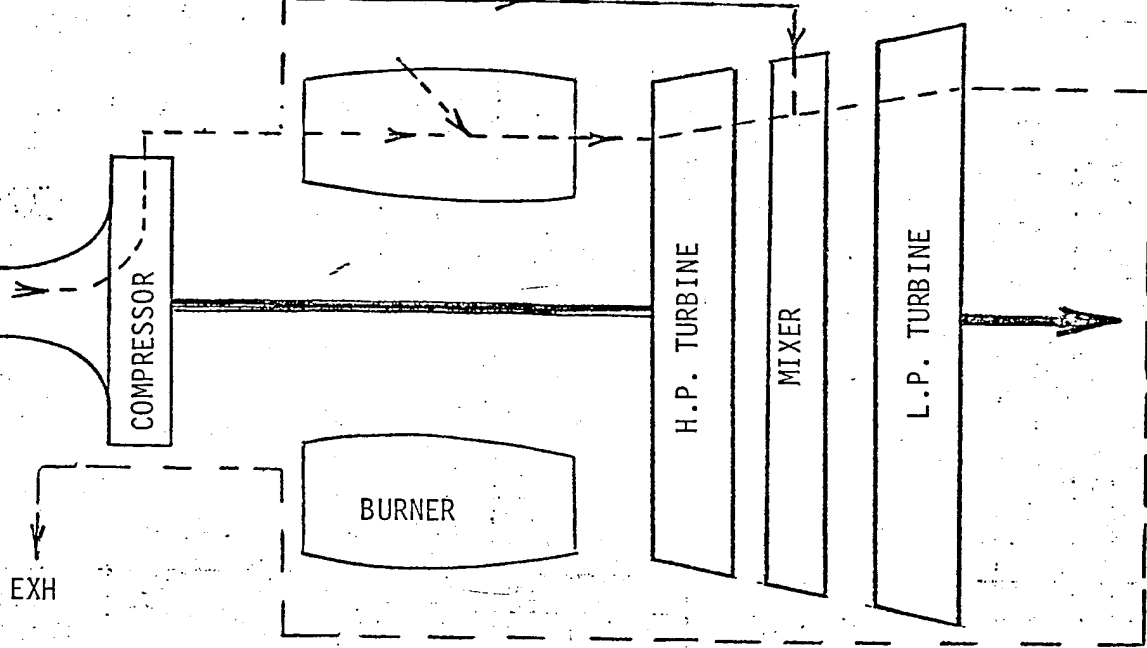
Fig. 3



All numbers are in percentage

EXERGY DISSIPATION FOR GTF40WR96

Fig. 4



ENERGY DISSIPATION FOR GTF990

Fig. 5

## Conclusions and Recommendations

The exergetic methods clearly indicate areas of exergy dissipation. As is well known, the two main dissipators are the burner and the exhaust stream. The use of the regenerator reduces the loss but not enough to feel that efforts can cease in that area. The quality of the energy in the exhaust stream, even with a regenerator, is still high. In addition to some of the other well known approaches to using the exhaust stream, it may be possible to combine some of it with the fuel forming a lower grade of combustible reactants which would still perform satisfactorily in the turbines. If feasible, this would certainly reduce some of the losses.

This approach can be effectively used to compare large energy users and it is recommended that present computer programs be modified to incorporate exergy calculations as well as those of energy.

APPENDIX A  
CALCULATIONS AND RESULTS  
GTF990 (C<sub>10</sub>H<sub>22</sub> as fuel)

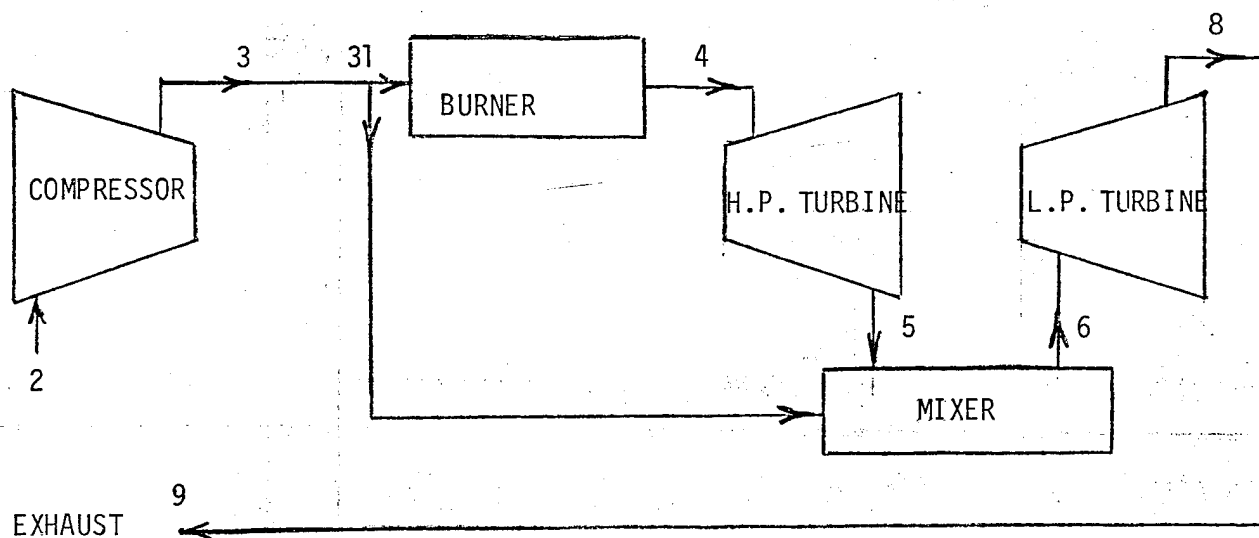
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81 111

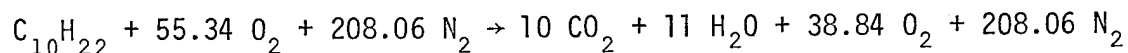
GAS TURBINE GTF990

For this analysis  $C_{10}H_{22}$  was used as the fuel.  $T_0 = 518.7^\circ R$ ,  $P_0 = 14.7$  psia  
F.A.R. = .0187  $\rightarrow$  357% of theoretical air.

The JANAF tables were used for the burner only. The calculator valves  
(derived from GAS TABLES) were used for all other calculations. The results  
were adjusted to make them consistent and then plotted.



Station	T °R	P	h	$\phi$	$-R \ln \frac{P}{14.7}$	S
1	518.7	14.7	123.93	1.5910	0	1.5910
2	518.7	14.7	123.93	1.5910	0	1.5910
3	1173.4	177.1	284.44	1.7904	-.1706	1.6198
4	2358.0	171.5	619.86	1.9883	-.1696	1.8187
5	1741.7	38.3	442.53	1.9014	-.0661	1.8353
6	1683.5	38.3	425.35	1.8911	-.0661	1.8250
8	1355.2	14.7	336.23	1.8323	0	1.8323
9	1355.2	14.7	336.23	1.8323	0	1.8323



Molecular Weight of Products

Using 357% theoretical air - 267.9 moles of products

	$x_i$	M	
CO <sub>2</sub>	.0373	44.01	1.6428
H <sub>2</sub> O	.0411	18.02	.7399
O <sub>2</sub>	.1450	32	4.6393
N <sub>2</sub>	.7766	28.01	<u>21.7519</u>

$$\hat{M} = 28.774 \text{ lb/lb mole of products}$$

PRELIMINARIES

$$ex = (h - T_0S) - (h_0 - T_0S_0)$$

For this calculation: Use  $T_0 = 518.7^\circ\text{R}$

$$P_0 = 14.7 \text{ psia}$$

Air  $h_0 = 123.93$

$$\phi_0 = S_0 = 1.5910 \quad \therefore h_0 - T_0S_0 = \underline{\underline{-701.32}} \text{ Air}$$

Prod. of Comb

FAR =  $h_0 = 124.78$

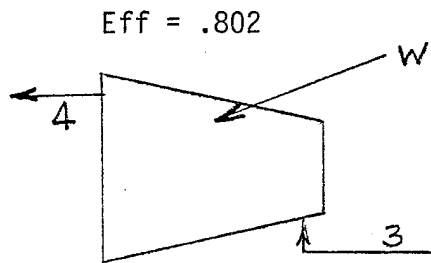
$$.0166 \quad \phi_0 = S_0 = 1.5912 \quad h_0 - T_0S_0 = \underline{\underline{-700.57}} \quad \text{FAR} = .0166$$

FAR =  $h_0 = 124.91$

$$.0187 \quad \phi_0 = S_0 = 1.5912 \quad h_0 - T_0S_0 = \underline{\underline{-700.4}} \quad \text{FAR} = .0187$$

STATION	$h - T_0S$	$-[h_0 - T_0S_0] = Ex$
1	-701.32	0
2	-701.32	0
3	-555.75	+145.57
4	-323.76	+376.55
5	-509.44	+190.96
6	-521.28	179.29
8	-614.18	86.39
9	-614.18	86.39

COMPRESSOR



$Ex_{comp} = ?$

$$\begin{aligned}
 W_{act} &= h_3 - h_2 \\
 &= 284.44 - 123.93 \\
 &= 160.51 \text{ B/lbm}
 \end{aligned}$$

$$E\dot{x}_2 + E\dot{x}_W = E\dot{x}_3 + E\dot{x}_D$$

$$m[(h_2 - T_0 S_2) - (h_0 - T_0 S_0)] + \dot{W} = \dot{m}[(h_3 - T_0 S_3) - (h_0 - T_0 S_0)] + E\dot{x}_D$$

$$[123.93 - 518.7 \times 1.5910] 43.5 + 43.5 (160.51) =$$

$$[(284.44 - 518.7 \times 1.6198)] 43.5 + E\dot{x}_D$$

$$(-701.32)(43.5) + 43.5 (160.51) = (-555.75) 43.5 + E\dot{x}_D$$

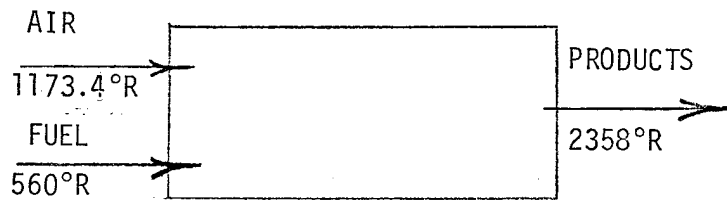
$$\underline{E\dot{x}_D = 649.9 \text{ B/s} \leftarrow}$$

$$E\dot{x}_2 = 43.5[(-701.32) - (-701.32)] = 0$$

$$E\dot{x}_W = (160.51)(43.5) = 6982.2 \text{ B/s}$$

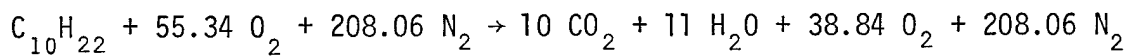
$$E\dot{x}_3 = 43.5[(-555.75) - (-701.32)] = 6332.3 \text{ B/s}$$

## COMBUSTOR (BURNER)

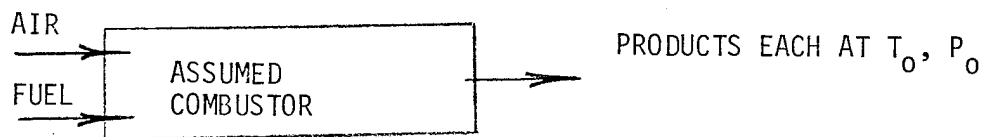


$$\text{FAR} = .0187 \quad \therefore 357\% \text{ Theoretical Air}$$

Combustion equation:



EXERGY OF REACTANTS



$$\sum_R \dot{n}_i [(h_f^\circ + \Delta h) - T_0 S] = \dot{E}x_R + \sum_P \dot{n}_j [(h_f^\circ + \Delta h) - T_0 S_0]$$

### REACTANTS

$$\text{C}_{10}\text{H}_{22}: 1 [-72.875 \times 1.8001 + (76.12)(23)] = -129,432\text{B} - T_0 S = -198,187\text{B}$$

$$T_0 S = 518.7 \left[ 3.9006 \frac{\text{kJ}}{\text{kg} \cdot ^\circ\text{K}} \times .4299 \times \frac{5}{9} \times 142.286 \right] = 68755$$

$$\text{O}_2 = \frac{55.34}{264.4} \times 177.1 = 37.07 \text{ psi}$$

$$\text{N} : = \frac{208.06}{264.4} \times 177.1 = 139.43 \text{ psi}$$

$$\text{O}_2: 55.34 \left[ 4704 - 518.7 \times \left( 54.72 - R \ln \frac{37.07}{14.7} \right) \right] = 1257593 \text{ Btu}$$

$$\text{N}: 208.06 \left[ 4506 - 518.7 \times \left( 51.267 - R \ln \frac{139.43}{14.7} \right) \right] = 4113071 \text{ Btu}$$

Products at  $T_0 P_0$  ( $H_2O$  liquid)

$$CO_2: 10[-169,297 + (-147) - 518.7 (50.74)] = -1,957,628$$

$$H_2O: 11[-122,971 + (-18 \times 18) - 518.7 (16.716 - .614)] = -1,448,118$$

$$\text{corr. for S: } .08775 - .05362 = -.3413 \frac{B}{lb} \times \frac{18 lb}{lb \text{ mole}} = .614$$

$$O_2: 38.84[0 + (-123) - 518.7 (48.725)] = -986,406$$

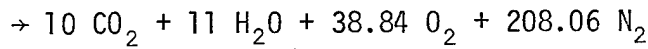
$$N_2: 208.06[0 + (-123) - 518.7 (45.492)] = \underline{-4935121}$$

$$\Sigma = 9327273$$

$$\therefore Ex_R \text{ of REACTANTS} = \underline{3,758,422} \text{ B/mole fuel}$$

$$= 26,415 \text{ B/lb fuel} = \underline{19018 \text{ B/s}}$$

EXERGY OF PRODUCTS



at  $T = 2358^\circ\text{R}$  and  $P = 171.5 \text{ psia}$

	$x_i$	$p_i = x_i P$	$R = 1.986 \frac{\text{Btu}}{\text{lbmole } ^\circ\text{R}}$
$\text{CO}_2$	.0373	6.36	
$\text{H}_2\text{O}$	.0411	7.05	
$\text{O}_2$	.1450	24.87	
$\text{N}_2$	.7766	133.19	

$$\text{CO}_2: 10[(-169,297 + 21,825) - 518.7 (67.943 - \bar{R} \ln \frac{6.36}{14.7})] = -1,835,771$$

$$\text{H}_2\text{O}: 11[(-104,036 + 16,932) - 518.7 (58.368 - \bar{R} \ln \frac{7.05}{14.7})] = -1,299,500$$

$$\text{O}_2: 38.84[(0 + 14,503) - 518.7 (60.48 - \bar{R} \ln \frac{24.87}{14.7})] = -634,114$$

$$\text{N}_2: 208.06[(0 + 13,700) - 518.7 (56.665 - \bar{R} \ln \frac{133.19}{14.7})] = -2,792,536$$

$$= -6,561,922 \text{ Btu}$$

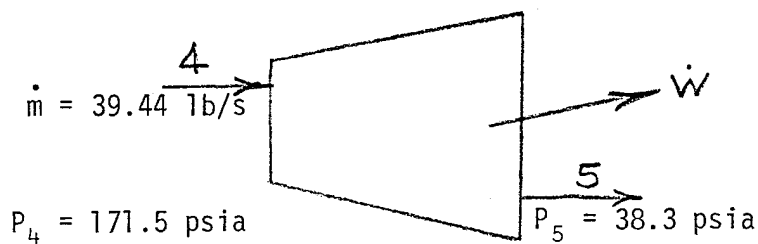
$$\text{Ex of Products} = (h - T_0 S) - (h_0 - T_0 S_0)_{T_0 P_0}$$

$$\text{Ex}_p = 2,765,350 \text{ B/mole fuel} = 19,435 \text{ B/lb fuel} = \underline{\underline{13,993 \text{ B/s}}}$$

$$\text{Ex}_{\text{Des}} \text{ in Combustor} = 3,758,422 - 2,765,350$$

$$= 993,072 \text{ B/mole fuel} = 6,979 \text{ B/lb fuel} = \underline{\underline{5025 \text{ B/s}}}$$

H. P. TURBINE



Assuming adiabatic & eff = .867

$$\text{eff} = .867 = \frac{W_{\text{act}}}{W_{\text{isen}}}$$

$$T_4 = 2358.0^\circ\text{R} \quad h_4 = 619.71 \quad \phi = 1.9883$$

$$P_5 = 38.3 \quad \text{if} \quad S_4 = S_5 = 1.9883 - \frac{1.986}{28.77} \frac{\text{B}}{\text{lbmole}} \ln \frac{171.5}{14.5}$$

$$S_4 = 1.8187 = 1.819$$

$$\frac{P_4}{P_5} = \frac{P_{r4}}{P_{r5}} : \frac{171.5}{38.3} = \frac{395.3}{P_{r5}} \quad \therefore P_{r5} = 88.3$$

2358

$$P_r @ 400\% = 385.1 \quad 47.3 \quad \therefore P_r = 395.3$$

$$200\% = 432.4$$

$$P_r = 88.3 @ 400\% \quad T = 1654 \quad T_s = 1647.6 \quad h_s = 416.4$$

$$200\% \quad T = 1624 \quad \phi = 1.8860$$

$$\text{Check} \quad S = 1.886 - \frac{1.986}{28.774} \ln \frac{38.3}{14.7} = 1.8199 \approx 1.820$$

$$W_s = 619.7 - 416.4 = 203.3$$

$$W_a = (-.867)(203.3) = 176.3 \text{ B/lb} \leftarrow$$

$$\text{From data} \quad W_a = 619.7 - 442.5 = 177.2 \leftarrow$$

$\therefore$  Data must assume adiabatic turbine.

H.P. TURBINE

$$\begin{aligned}\dot{E}x_4 &= (h_4 - T_0 S_4) - (h_0 - T_0 S_0) \\ &= [(619.71 - 518.7 \times 1.819) - (-700.4)] \times 39.44 \\ &= 14,853 \text{ B/s}\end{aligned}$$

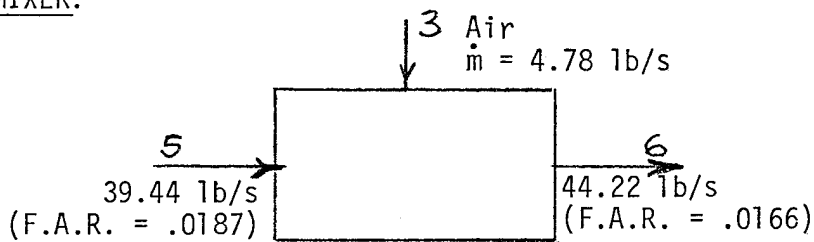
$$\dot{E}x_W = (177.2)(39.44) = 6989 \text{ B/s}$$

$$\dot{E}x_5 = 39.44[442.53 - 518.7 \times 1.835 - (-700.4)] = 7533 \text{ B/s}$$

$$\therefore 14,853 = 6989 + 7533 + \dot{E}x_D$$

$$\underline{\underline{\dot{E}x_D = 331 \text{ B/s}}}$$

MIXER:



$$\dot{E}x_3 = 4.78 [(-555.75) - (-701.32)] = 696 \text{ B/s}$$

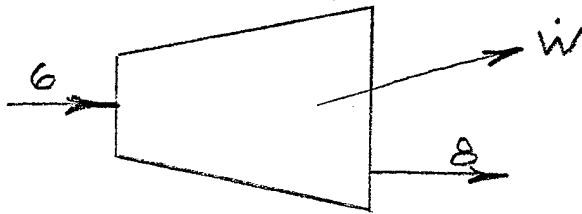
$$\dot{E}x_5 = 7533 \text{ B/s}$$

$$\begin{aligned}\dot{E}x_6 &= 44.22 [(425.35) - (518.7)(1.825) - (-700.57)] \\ &= 7928 \text{ B/s}\end{aligned}$$

$$\therefore 7533 + 696 = 7928 + \dot{E}x_D$$

$$\therefore \underline{\underline{\dot{E}x_D = 301 \text{ B/s}}}$$

L.P. TURBINE



$$W = h_6 - h_8 = 425.35 - 336.23 = 89.12 \text{ B/lb}$$

$$\dot{W} = 44.22 \times 89.12 = 3932 \text{ B/s}$$

$$\dot{E}x_W = 3932 \text{ B/s}$$

$$\dot{E}x_6 = 7928 \text{ B/s}$$

$$\dot{E}x_8 = 44.22 [(336.23 - 518.7 \times 1.8323) - (-700.57)]$$

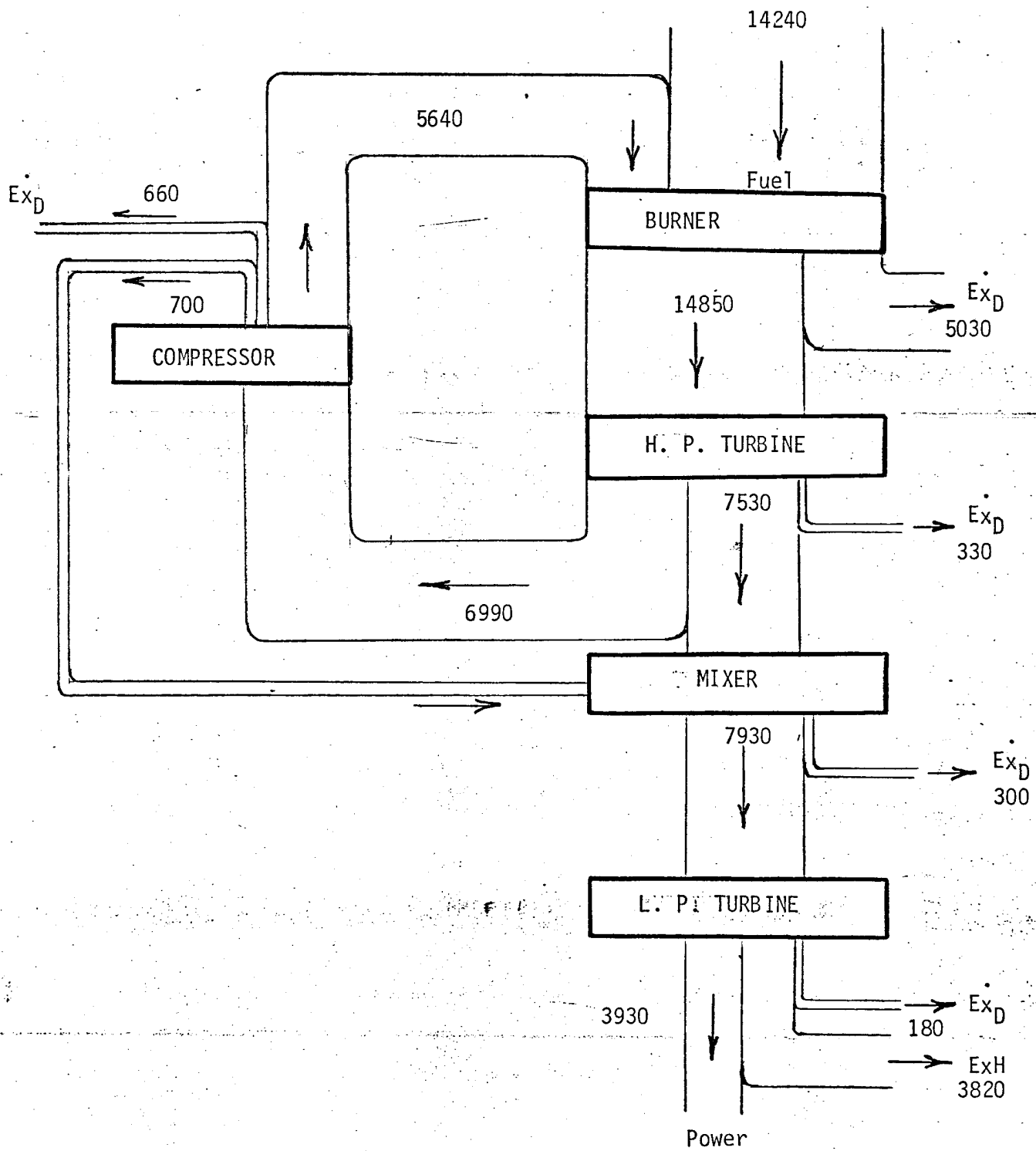
$$= 3820 \text{ B/s} \quad \text{To Dif \& Exhaust}$$

$$\therefore 7928 = 3932 + 3820 + \dot{E}x_D$$

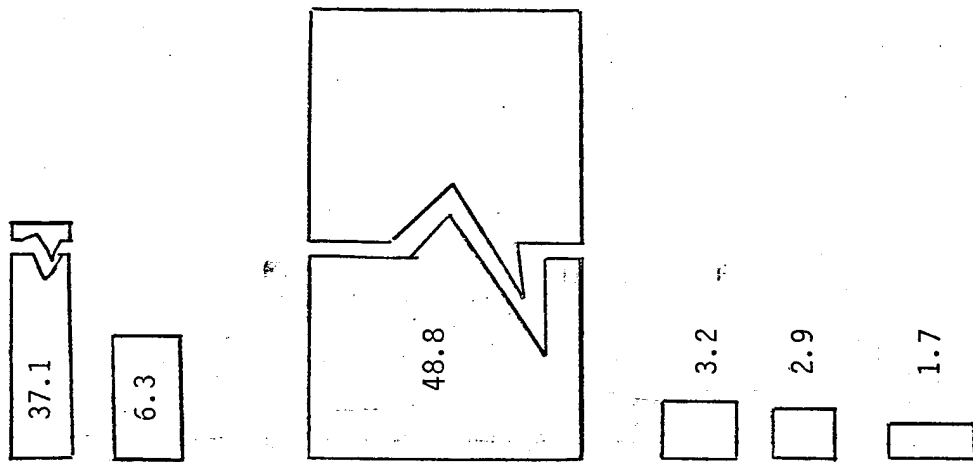
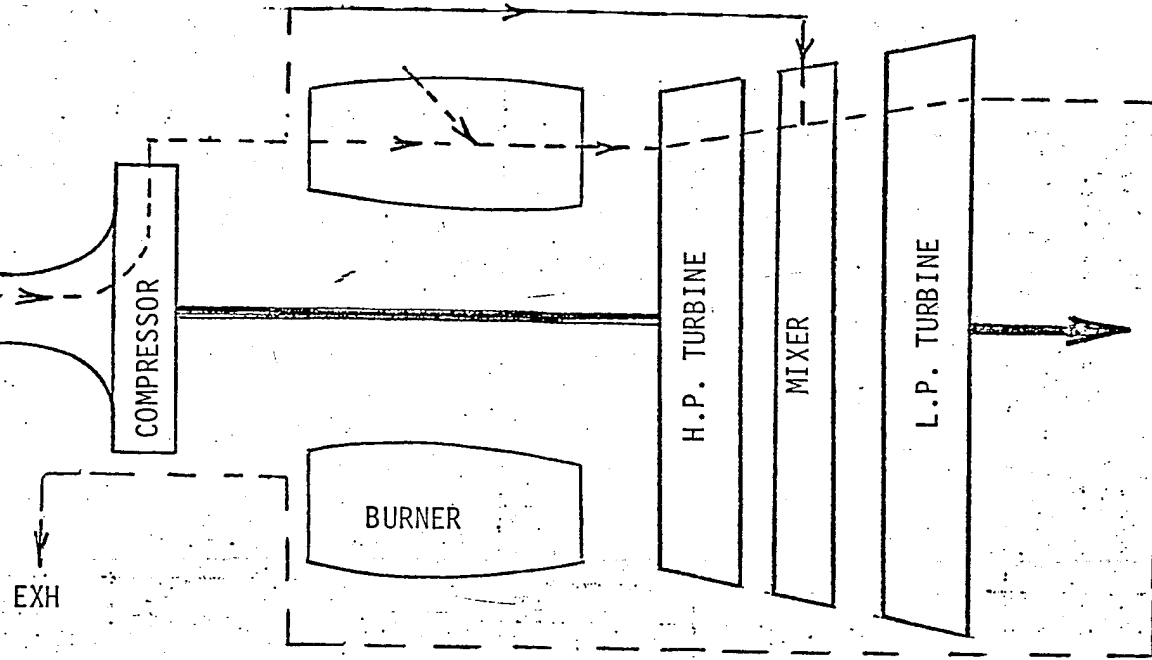
$$\underline{\underline{\dot{E}x_D = 176 \text{ B/s}}}$$

EXERGY DISSIPATED

		Percent
COMP	650	6.31
BURNER	5025	48.77
H.P. TURBINE	331	3.21
MIXER	301	2.92
L.P. TURBINE	176	1.71
DIF & EXHAUST	<u>3820</u>	<u>37.08</u>
	10303 B/s	100.00



EXERGY FLOW GTF990  
(All Units BTU/S)



All numbers are in percentage

EXERGY DISSIPATION FOR GTF990

APPENDIX B

CALCULATIONS AND RESULTS

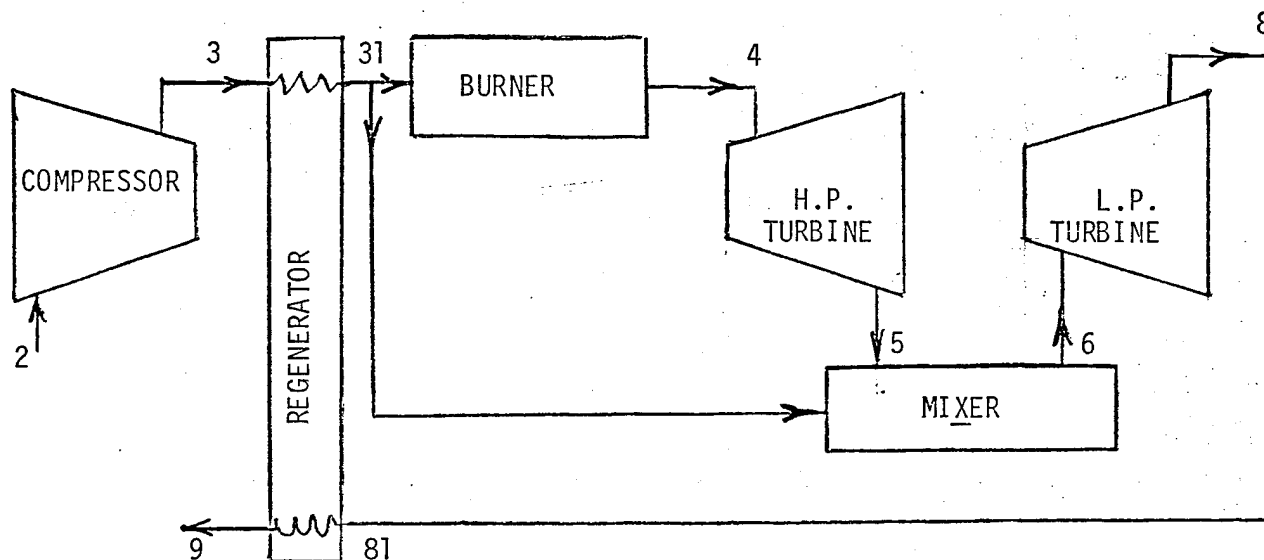
GTF990WR<sub>86</sub> (C<sub>10</sub>H<sub>22</sub> as fuel)

Using  $C_{10}H_{22}$  Fuel

GTF990WR86

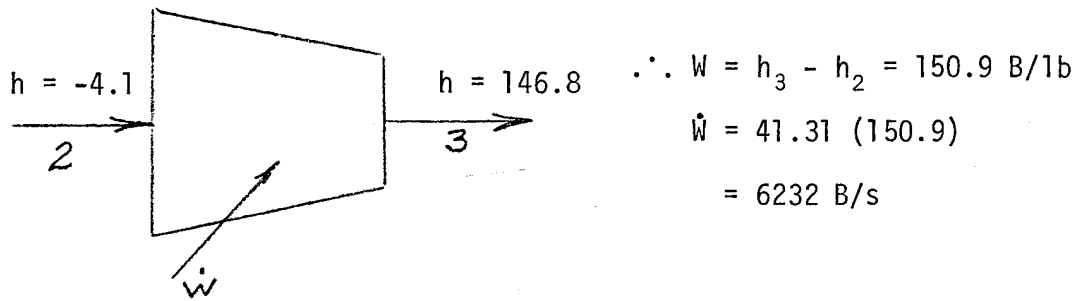
JANAF DATA

AMBIENT 518.7°R & 14.7 psia



STA	P Psia	T °R	Rel to STP h B/lbm	$\dot{m}$ lb/s	Rel to 0° $\phi$ B/lb-R	$R \ln \frac{P}{14.7}$	S
2	14.7	518.7	-4.1	41.31	1.5910	0	1.5910
3	160.7	1129.7	146.8	41.31	1.7808	.1639	1.6169
31	154.2	1362.6	206.4	36.77	1.8287	.1611	1.6676
4	149.2	2358.0		37.35	1.9868	.1598	1.8270
5	38.0	1780.9		37.35	1.9065	.0655	1.8410
6	38.0	1714.1		41.90	1.8952	.0655	1.8297
8	15.4	1400.4		41.90	1.8403	.0033	1.8370
81	15.4	1400.4		41.90	1.8403	.0033	1.8370
9	14.7	1197.1		41.90	1.7990	0	1.7990

COMPRESSOR



EXERGY BALANCE

$$\dot{E}x_2 + \dot{E}x_W = \dot{E}x_3 + \dot{E}x_D$$

$$S_2 = 1.5910 - R \ln 1 = 1.5910$$

$$S_3 = 1.7808 - .06855 \ln \frac{160.7}{14.7} = 1.6169$$

$$h_0 - T_0 S_0 \text{ (@ } 14.7, 518.7^\circ\text{R)} = -4.1 - 518.7 \times 1.5910 = -829.35 \text{ B/lb}$$

$$\dot{E}x_2 = 0$$

$$\dot{E}x_3 = \{ [146.8 - 518.7 \times 1.6169] - [-829.35] \} \{ 41.31 \} = 5678.6 \text{ B/s}$$

$$\dot{E}x_W = 6232 \text{ B/s}$$

$$\therefore 0 + 6232 = 5678.6 + \dot{E}x_D$$

$$\underline{\underline{\dot{E}x_D = 553.0 \text{ B/s}}}$$

$$\text{Cal/gm mole } ^\circ\text{K} \times 1.8001 \frac{\text{Btu/lb mole}}{\text{cal/gm mole}} \frac{5^\circ\text{K}}{9^\circ\text{R}} \times \frac{1 \text{bmole}}{28.964 \text{ lbm}}$$

$$\therefore S^\circ \text{ @ } 518.7^\circ\text{R} = 45.99 \text{ Cal/gmole}^\circ\text{K} = 1.588 \text{ OK}$$

$$h \text{ @ } 518.7 \text{ rel to } 537$$

$$= -.065 \frac{\text{h cal}}{\text{gmole}} \times \frac{1.8001}{10^{-3} \frac{\text{h cal}}{\text{cal}}} \times \frac{1}{28.964} = -4.07 \text{ B/lbm}$$

h @ 1129.7°R

$$= 2.322 \frac{\text{kcal}}{\text{gmole}} = 146.8 \text{ B/lbm}$$

h @ 1362.6 @ 31

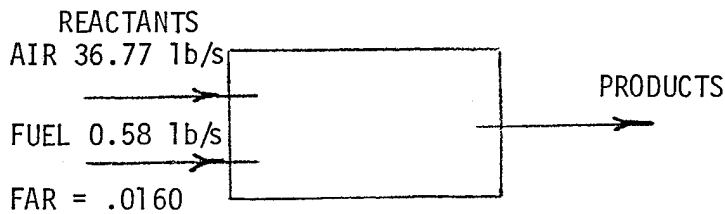
$$3.321 \frac{\text{hcal}}{\text{gmole}} = 206.4 \text{ B/lbm}$$

AT 31 out of HX

$$\dot{E}_x = \{(206.4 - 518.7 \times 1.6676) - (-829.35)\} 41.31$$

$$\underline{\underline{\dot{E}_x = 7054 \text{ B/s}}}$$

BURNER

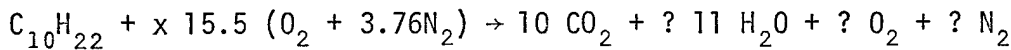


Assume  $C_{10}H_{22}$  fuel LHV = 19,020 B/lb

$$T_{fuel} = 100^\circ F$$

$$C_p = .535 \text{ B/lb } ^\circ R = 76.12 \text{ B/lbmole-}^\circ R$$

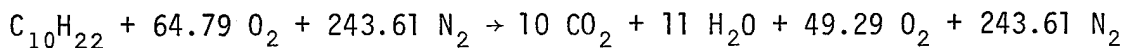
Air Temp = 1362.6 $^\circ R$



$$.0160 = \frac{(1)(142.286)}{x(15.5)(32) + x(15.5)(3.76)(28.016)}$$

$$x = 4.18 \quad \therefore 418\% \text{ theoretical Air}$$

$\therefore$



$$E\dot{x}_R = E\dot{x}_P + E\dot{x}_D$$

$H_R$ :

$$C_{10}H_{22}: 1[(-131\ 183) + 76.13(23)] = -129\ 432$$

$$O_2: 64.79[0 + 6197] = 401\ 504$$

$$N_2: 243.61[0 + 5898] = 1\ 436\ 812$$

$$S_{C_{10}H_{22}} = 3.9006 \times \frac{1}{4.187} \times 142.286 = 132.553 \text{ B/lbmole } ^\circ R$$

$$O_2: x_i = .21 \quad \therefore p_{O_2} = .21 \times 154.2 = 32.38 \text{ psia} \quad \therefore S_{O_2} = 55.9 - 1.986 \ln \frac{32.38}{14.7} = 54.33$$

$$N_2: x_i = .79 \therefore p_{N_2} = .79 \times 154.2 = 121.82 \text{ psia} \therefore S_{N_2} = 52.374 - 1.986 \ln \frac{121.82}{14.7} = 48.174$$

	$H_R$	S	$-nT_0S$	$H_R - T_0S$
$C_{10}H_{22}$	-129432	132.553	-68755	-198 187
$O_2$	+401504	54.33	-1825845	-1424341
$N_2$	+1436812	48.174	-6087291	-4650479

$$\Sigma H_R - T_0S = -6273007 \text{ Btu}$$

$H_0 - T_0S_0$  of Products at STP

$$CO_2: 10[-169,297 + (-147) - 518.7 (50.742)] = -1957 639$$

$$H_2O (l): 11[-122971 + (-18 \times 18) - 518.7 (16.716 - .614)] = -1448 118$$

$$O_2: 49.29[0 + (-123) - 518.7 (48.725)] = -1 251 801$$

$$N_2: 243.61[0 + (-123) - 518.7 (45.492)] = -5 778 356$$

$$(H_0 - T_0S_0)_{STP} = -10 435 914 \text{ Btu}$$

$$Ex_R = 4162 907 \text{ B/mole fuel}$$

$$\dot{m} = .58 \frac{\text{lb}_{\text{fuel}}}{\text{s}} \times \frac{\text{mole}_{\text{fuel}}}{142.286 \text{ lb}_{\text{fuel}}}$$

$$\therefore \underline{\underline{\dot{Ex}_R = 16 969 \text{ B/s}}}$$

PRODUCTS

$$\text{CO}_2: 10[(-169297 + 21825) - 518.7 (70.183)] = -1838759$$

$$\text{H}_2\text{O}: 11[(-104036 + 16932) - 518.7 (60.423)] = -1302900$$

$$\text{O}_2: 49.29[(0 - 14504) - 518.7 (59.554)] = -807698$$

$$\text{N}_2: 243.61 [(0 + 13700) - 518.7 (52.566)] = -3304809$$

ENTROPIES:

		$p_i$ (psia)	$-R \ln P/14.7$	$\phi$	S
$x_{\text{CO}_2} = 10/313.9 = .0319$		4.759	2.240	67.943	70.183
$\text{H}_2\text{O} \quad 11/313.9 = .0350$		5.222	2.055	58.368	60.4238
$\text{O}_2 \quad 49.29/313.9 = .1570$		23.424	-.925	60.479	59.554
$\text{N}_2 \quad 243.61/313.9 = .7761$	115.794		-4.099	56.665	52.566

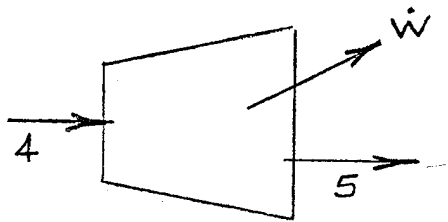
$$(H - T_0 S)_P = -7254167$$

$$Ex_P = (H - T_0 S)_P - (H_0 - T_0 S_0)_{STP} = 3181747 \text{ B/mole fuel}$$

$$Ex_P = 12970 \text{ B/s} = Ex_4$$

$$16969 - 12970 = Ex_D = \underline{\underline{3999 \text{ B/s} \quad \text{BURNER}}}$$

H.P. TURBINE



$$T_5 = 1780.9^\circ\text{R}, P_5 = 38.0 \text{ psia}$$

$$h_5 - h_4 = 1530985 \text{ B/mole fuel}$$

from pg 6 & 7 below.

$$\dot{W} = 6240 \text{ B/s}$$

Ex<sub>5</sub>

$$\text{CO}_2: 10[-169.297 + 11825 - 518.7 (69.157)] = -1933437$$

$$\text{H}_2\text{O}: 11[-104036 + 10991 - 518.7 (60.256)] = -1367298$$

$$\text{O}_2: 49.29[0 + 9611 - 518.7 (59.891)] = -1057490$$

$$\text{N}_2: 243.61[0 + 9084 - 518.7 (53.038)] = -4488955$$

$$\Sigma = -8847181 \text{ Btu}$$

	$p_i$	$-R \ln P/14.7$	$\phi$	S
CO <sub>2</sub>	1.212	4.956	64.201	69.157
H <sub>2</sub> O	1.330	4.772	55.484	60.256
O <sub>2</sub>	5.966	1.791	58.100	59.891
N <sub>2</sub>	29.492	-1.383	54.421	53.038

$$\text{Ex}_5 = -8847181 - (-10\,435\,914) = 1588733 \text{ B/mole fuel}$$

$$\text{CO}_2 \quad .0319 \quad 44.011 \quad 1.404$$

$$\text{H}_2\text{O} \quad .0350 \quad 18.016 \quad .631$$

$$\text{O}_2 \quad .1570 \quad 32.00 \quad 5.024$$

$$\text{N}_2 \quad .7761 \quad 28.016 \quad 21.743$$

$\hat{M} = 28.8 \text{ lb/mole}$   
(not needed at this time)

$$\therefore \text{Ex}_5 = 1588733 \times .58 \times \frac{1}{142.286} = 6476 \text{ B/s}$$

$$12970 = 6240 + 6476 + \dot{\text{Ex}}_D \quad \therefore \dot{\text{Ex}}_D = 254 \text{ B/s}$$

H.P. TURBINE (CHECK)

Using Calculator Program

$$(H - T_0 S)_4 - (H_0 - T_0 S_0)_{4, \text{STP}} = (H - T_0 S)_5 - (H_0 - T_0 S_0)_{5, \text{STP}} + \dot{W} + \dot{E}x_D$$

$$H_4 - H_5 - T_0 (S_4 - S_5) = \dot{W} + \dot{E}x_D$$

$$\dot{E}x_D = T_0 (S_5 - S_4)$$

$S_5$  @ 1780.9°R & 38 psia

$$\phi_5 = 1.9065 \text{ B/lbm} - \frac{1.986}{28.802} \ln \frac{38}{14.7} = - .0655$$

$$S_5 = 1.8410 \text{ B/lbm}$$

$S_4$  @ 2358°R & 149.2 psia

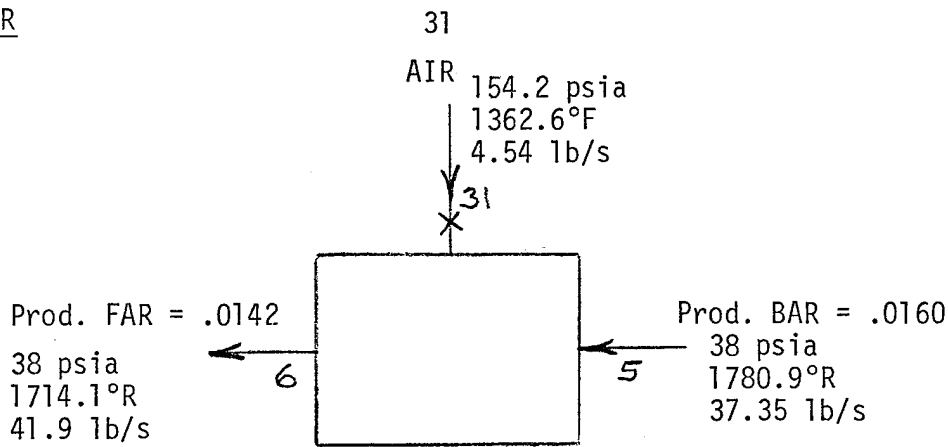
$$\phi_4 = 1.9868 - \frac{1.986}{28.802} \ln \frac{149.2}{14.7} = - .1598$$

$$S_4 = 1.8270$$

$$\therefore \dot{E}x_D = (37.35)(518.7)(1.841 - 1.827)$$

$$\underline{\underline{\dot{E}x_D = 270 \text{ B/s}}} \quad \text{close enough}$$

MIXER



For a FAR = .0142 must add  $x(O_2 + 3.76 N_2)$

$$.0142 = \frac{142.286}{x(15.5)(32) + x(15.5)(3.76)(28.016)} \quad \therefore x = 4.707$$

$$72.96 O_2 - 64.79 O_2 = 8.17 O_2$$

$$274.32 N_2 - 243.61 N_2 = 30.71 N_2$$

$\therefore$  AIR

$$(8.17 O_2 + 30.71 N_2) + 10 CO_2 + 11 H_2O + 49.29 O_2 + 243.6 IN_2$$

$$\rightarrow 10 CO_2 + 11 H_2O + 57.46 O_2 + 274.32 N_2$$

$$Ex_{air} \quad 31 \quad (206.4 - 518.7 \times 1.6676) - (-829.35)$$

$$\phi = 1.8287 \quad S = 1.6675$$

$$Ex_{air} = 170.76 \text{ B/lb}$$

$$\underline{\underline{\dot{E}x_{air} = 775 \text{ B/s}}}$$

$$\underline{\underline{\dot{E}x_5 = 6476 \text{ B/s}}}$$

Ex<sub>6</sub>

	n	x <sub>i</sub>	M	lb/mole mix	P <sub>i</sub>
CO <sub>2</sub>	10	.0283	44.011	1.2475	1.075
H <sub>2</sub> O	11	.0312	18.016	0.5618	1.186
O <sub>2</sub>	57.46	.1629	32	5.2121	6.190
N <sub>2</sub>	$\frac{274.32}{352.78}$	.7776	28.016	$\frac{21.7851}{28.807}$	29.549

$$\hat{M} = 28.81$$

	φ	-R ln P <sub>i</sub> /14.7	S	Δh
CO <sub>2</sub>	63.699	5.194	68.893	13270
H <sub>2</sub> O	55.104	4.999	60.103	10344
O <sub>2</sub>	57.776	1.718	59.494	9058
N <sub>2</sub>	54.118	-1.387	52.731	8567

$$\text{CO}_2: 10[-169297 + 13270 - 518.7 (68.893)] = -1917618$$

$$\text{H}_2\text{O}: 11[-104036 + 10344 - 518.7 (60.103)] = -1373542$$

$$\text{O}_2: 57.46[0 + 9058 - 518.7 (59.494)] = -1252716$$

$$\text{N}_2: 274.32[0 + 8567 - 518.7 (52.731)] = -5152983$$

$$\Sigma = (H - T_0 S)_6 = -9696859 \text{ Btu}$$

H<sub>0</sub> - T<sub>0</sub>S<sub>0</sub> at STP

$$\text{CO}_2: 10[-169297 + (-147) - 518.7 (50.742)] = 01957639$$

$$\text{H}_2\text{O}: 11[-122971 + (-324) - 518.7 (16.716 - .614)] = -1448118$$

$$\text{O}_2: 57.46[0 + (-123) - 518.7 (48.725)] = -1459292$$

$$\text{N}_2: 274.32[0 + (-123) - 518.7 (45.492)] = 06506788$$

Ex<sub>6</sub>

	n	x <sub>i</sub>	M	lb/mole mix	P <sub>i</sub>
CO <sub>2</sub>	10	.0283	44.011	1.2475	1.075
H <sub>2</sub> O	11	.0312	18.016	0.5618	1.186
O <sub>2</sub>	57.46	.1629	32	5.2121	6.190
N <sub>2</sub>	$\frac{274.32}{352.78}$	.7776	28.016	$\frac{21.7851}{28.807}$	29.549

$$\hat{M} = 28.81$$

	φ	-Rln P <sub>i</sub> /14.7	S	Δh
CO <sub>2</sub>	63.699	5.194	68.893	13270
H <sub>2</sub> O	55.104	4.999	60.103	10344
O <sub>2</sub>	57.776	1.718	59.494	9058
N <sub>2</sub>	54.118	-1.387	52.731	8567

$$\text{CO}_2: 10[-169297 + 13270 - 518.7 (68.893)] = -1917618$$

$$\text{H}_2\text{O}: 11[-104036 + 10344 - 518.7 (60.103)] = -1373542$$

$$\text{O}_2: 57.46[0 + 9058 - 518.7 (59.494)] = -1252716$$

$$\text{N}_2: 274.32[0 + 8567 - 518.7 (52.731)] = -5152983$$

$$\Sigma = (H - T_0 S)_6 = -9696859 \text{ Btu}$$

H<sub>0</sub> - T<sub>0</sub>S<sub>0</sub> at STP

$$\text{CO}_2: 10[-169297 + (-147) - 518.7 (50.742)] = 01957639$$

$$\text{H}_2\text{O}: 11[-122971 + (-324) - 518.7 (16.716 - .614)] = -1448118$$

$$\text{O}_2: 57.46[0 + (-123) - 518.7 (48.725)] = -1459292$$

$$\text{N}_2: 274.32[0 + (-123) - 518.7 (45.492)] = 06506788$$

Line 6 con't

$$\Sigma = - 11371837 \text{ B} = H_0 - T_0 S_0 \text{ at STP}$$

for FAR = .0142

$$(H - T_0 S) - (H_0 - T_0 S_0) = - 9696859 - (-11371837)$$

$$Ex_6 = 1674978 \text{ B}/352.78 \text{ moles}$$

$$= 4748 \text{ B/mole} \times \frac{\text{mole}}{28.81 \text{ lb/mole}} \times 41.9 \frac{\text{lb}}{\text{s}}$$

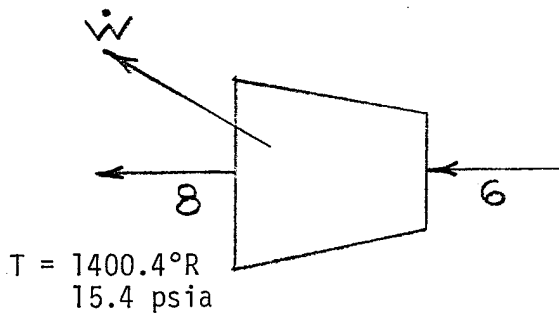
$$\underline{\underline{\dot{E}x_6 = 6905 \text{ B/s}}}$$

∴ FOR MIXER

$$775 + 6476 = 6905 + \dot{E}x_D$$

$$\underline{\underline{369 \text{ B/s} = \dot{E}x_D}}$$

L.P. TURBINE



$$\dot{W} = (\Delta h) \dot{m}$$

$$\Delta h = 874050 \text{ B}/352.78 \text{ moles}$$

$$\dot{W} = 3603 \text{ B/s}$$

$\dot{Ex}_8$

	$S^\circ = \phi$	$\Delta h$	$P_i$	$-R \ln P_i/14.7$	$S$
$\text{CO}_2$	61.167	9337	.436	6.987	68.154
$\text{H}_2\text{O}$	53.197	7380	.480	6.794	59.991
$\text{O}_2$	56.127	6499	2.509	3.511	59.638
$\text{N}_2$	52.580	6179	11.975	.407	52.987

$H - T_0 S$

$$\text{CO}_2: 10[-169297 + 9337 - 518.7 (68.154)] = -1953115$$

$$\text{H}_2\text{O}: 11[-104036 + 7380 - 518.7 (59.991)] = -1405506$$

$$\text{O}_2: 54.76[0 + 6499 - 518.7 (59.638)] = -1404048$$

$$\text{N}_2: 274.32[0 + 6179 - 518.7 (52.987)] = -5844486$$

$$H - T_0 S = -10607155$$

$$Ex_8 = -10607155 - (-11371837) = 764682 \text{ B}$$

$$\dot{Ex}_8 = 764682 \times \frac{1}{352.78} \times \frac{1}{28.81} \times 41.9$$

$$\dot{Ex}_8 = 3152 \text{ B/s}$$

$$6905 = 3603 + 3152 + Ex_D$$

$$\underline{\underline{Ex_D = 150 \text{ B/s}}}$$

HEAT EXCHANGER

$$T_9 = 1197.1^\circ\text{R} \quad P_9 = 14.7$$

LINE	9	$-R \ln \frac{P_i}{14.7}$	S	$\Delta h$
CO <sub>2</sub>	59.287	7.080	66.367	6913
H <sub>2</sub> O	51.774	6.886	58.660	5548
O <sub>2</sub>	54.878	3.604	58.482	4889
N <sub>2</sub>	51.414	,500	51.914	4677

$$\text{CO}_2: 10[-169297 + 6913 - 518.7 (66367)] = -1968086$$

$$\text{H}_2\text{O}: 11[-104036 + 5548 - 518.7 (58.660)] = -1418064$$

$$\text{O}_2: 57146[0 + 4889 - 518.7 (58.482)] = -1462105$$

$$\text{N}_2: 274.32[0 + 4677 - 518.7 (51.914)] = -6103837$$

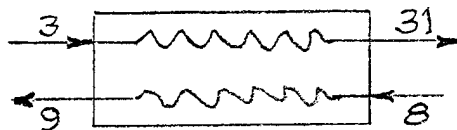
$$(H - T_0 S)_9 = -10952092 \text{ Btu}$$

$$(H_0 - T_0 S_0) = -11371837 \text{ Btu}$$

$$Ex_9 = 419745 \text{ Btu}$$

$$E\dot{x}_9 = 419745 \times \frac{1}{352.78} \times \frac{1}{28.81} \times 41.9$$

$$E\dot{x}_9 = 1730 \text{ B/s}$$

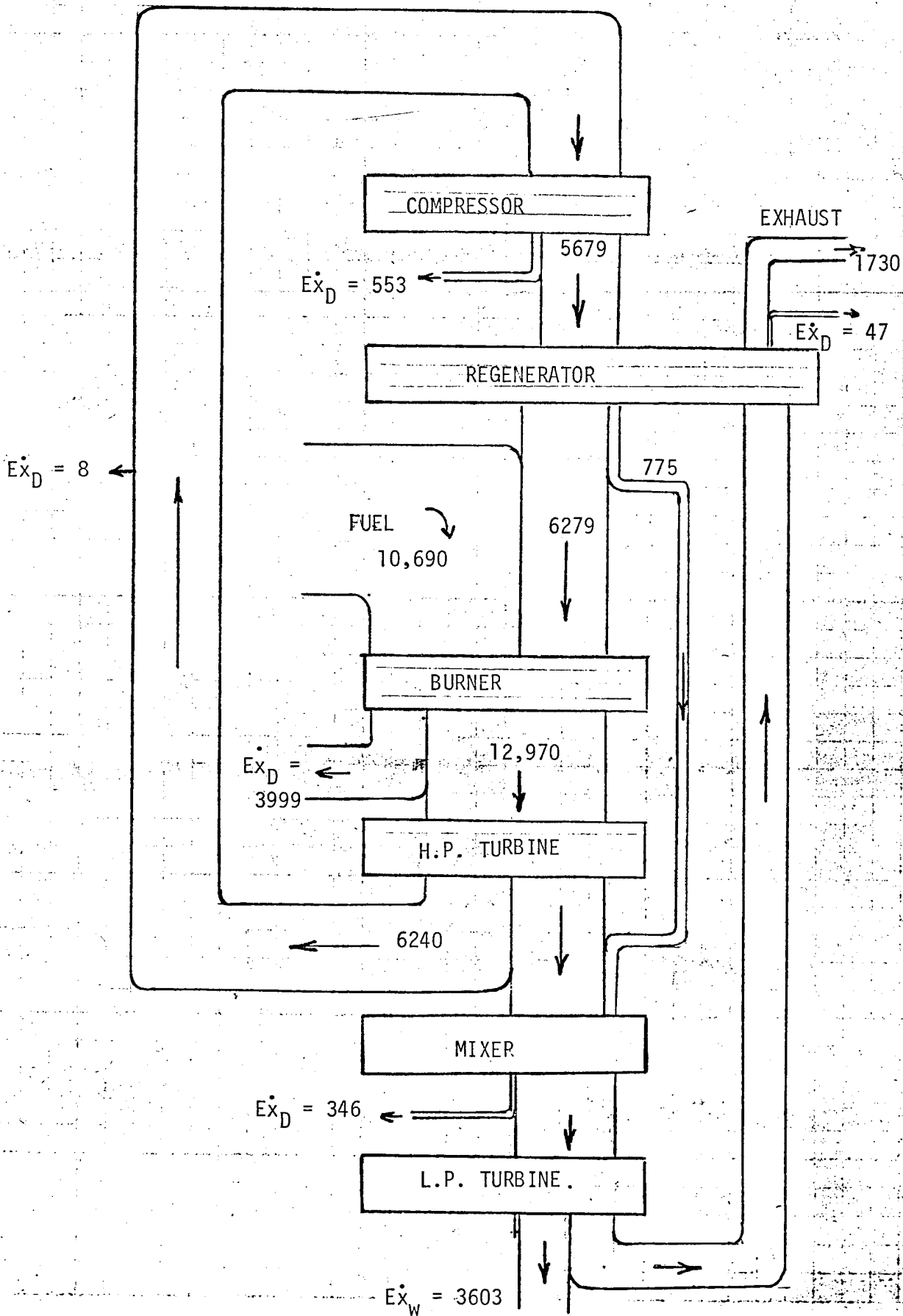


$$E\dot{x}_3 + E\dot{x}_8 = E\dot{x}_{31} + E\dot{x}_9 + E\dot{x}_D$$

$$5679 + 3152 = 7054 + 1730 + E\dot{x}_D$$

$$E\dot{x}_D = 47 \text{ B/s}$$

EXERGY FLOW DIAGRAM  
(All values in Btu/s)



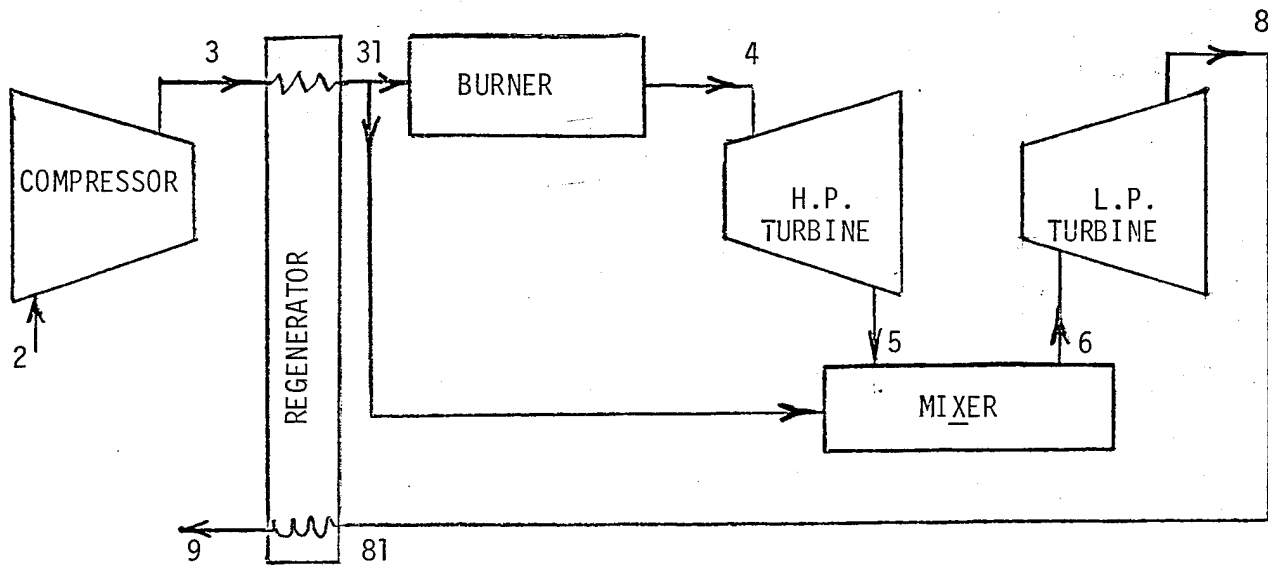
APPENDIX C

CALCULATIONS AND RESULTS

GTF990WR<sub>86</sub> and GTF40WR<sub>86</sub> (LHV = 18,400 Btu/lbm)

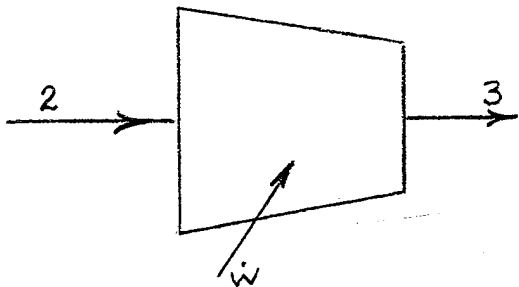
## USING GAS TABLES

Ambient 518.7°R &amp; 14.7 psia; REF. EFF = .86; L.H.V. = 18,400 Btu/lbm



STA	P Psia	T °R	h Btu/lbm	$\dot{m}$ lbm/s	$\phi$	R&n P/14.7	S
2	14.7	418.7	123.93	41.31	1.5910		1.5910
3	160.7	1129.7	273.10	41.31	1.7808	.1639	1.6169
31	154.2	1362.6	332.70	36.77	1.8287	.1611	1.6676
4	149.2	2358.0	617.52	37.35	1.9868	.1598	1.8270
5	38.0	1780.0	452.14	37.35	1.9065	.0655	1.8410
6	38.0	1714.1	432.69	41.90	1.8952	.0655	1.8297
8	15.4	1400.4	347.47	41.90	1.8403	.0033	1.837
81	15.4	1400.4	347.47	41.90	1.8403	.0033	1.8370
9	14.7	1197.1	293.97	41.90	1.7990	0	1.7990

COMPRESSOR



$$\dot{W} = 6162.2 \text{ Btu/s}$$

$$\dot{m} = 41.31 \text{ lbm/s}$$

$$\dot{E}x_2 + \dot{E}x_W = \dot{E}x_3 + \dot{E}x_D$$

$$\dot{E}x_2 = 0$$

$$\dot{E}x_W = 6162.2 \text{ Btu/s}$$

$$h_o - T_o S_o = 123.93 - 518.7 \times 1.5910$$

$$= -701.32 \text{ Btu/lbm (@14.7 \& 518.7^\circ\text{R})}$$

$$\dot{E}x_3 = \{[273.1 - 518.7 \times 1.6169] - [-701.32]\}(41.31)$$

$$= 5607.2 \text{ Btu/s}$$

$$\therefore 0 + 6162.2 = 5607.2 \dot{E}x_D$$

$$\underline{\underline{\dot{E}x_D = 555 \text{ Btu/s}}}$$

$$\dot{E}x_{31} \text{ (out of HX)}$$

$$\dot{E}x = \{[33].7 - 518.7 \times 1.6676\} - [-701.32]\}(41.31)$$

$$\dot{E}x_{31} = 6983 \text{ Btu/s}$$

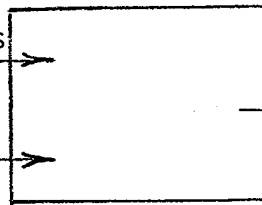
# BURNER

$$T_a = 518.7^\circ\text{R}$$

Air 36.77 lb/s

Fuel .58 lb/s

$$T \approx 537$$



$$T_{\text{air}} = 1362.6^\circ\text{R}$$

$$T_o = 518.7^\circ\text{R}$$

$$\text{LHV} = 18400 \text{ Btu/lbm}$$

$$S^\circ_{\text{fuel}} = .9 \text{ Btu/lbm } ^\circ\text{R}$$

$$\dot{E}\dot{x}_D = \dot{m}_f (\text{LHV}) + \dot{m}_f (\Delta h_f - T_o S_f) + \dot{m}_{\text{air}} \left( \frac{\Delta h - T_o S}{T_a - 537} \right)_{\text{air}} - \dot{m}_p (\Delta h_p - T_o S)_p$$

$$\dot{m}_f (\text{LHV}) = (.58)(18,400) = \underline{10672 \text{ B/s}}$$

$$\Delta h_f \approx 0, \quad T_o S_f = (518.7)(.9) = 467 \text{ B/lb}; \quad \dot{m}_f ( ) = 271 \text{ B/s}$$

$$\Delta h_{\text{air}} = (333 - 128) = 205 \text{ B/lbm}; \quad T_o S = 518.7 \times 1.6676 = 865 \text{ B/lbm}$$

$$\therefore \dot{m}_{\text{air}} (\Delta h - T_o S) = -24266 \text{ B/s}$$

$$\Delta h_p = (617.5 - 129.2) = 488.3 \text{ B/lbm}; \quad T_o S_p = 518.7 \left( 1.9868 - R \&n \frac{149.2}{14.7} \right)$$

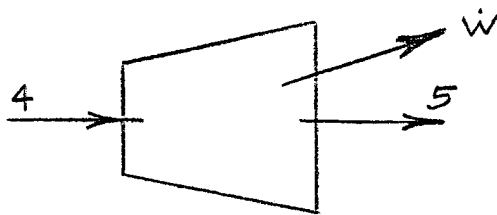
$$T_o S_p = 518.7 (1.9868 - .1598) = 947.7 \text{ B/lb}$$

$$\dot{m}_p (\Delta h_p - T_o S)_p = 37.35 (488.3 - 947.7) = -17157 \text{ B/s}$$

$$\dot{E}\dot{x}_D = 10672 - 271 + (-24266) - (-17157)$$

$$\underline{\underline{\dot{E}\dot{x}_D = 3292 \text{ B/s}}}$$

H.P. TURBINE



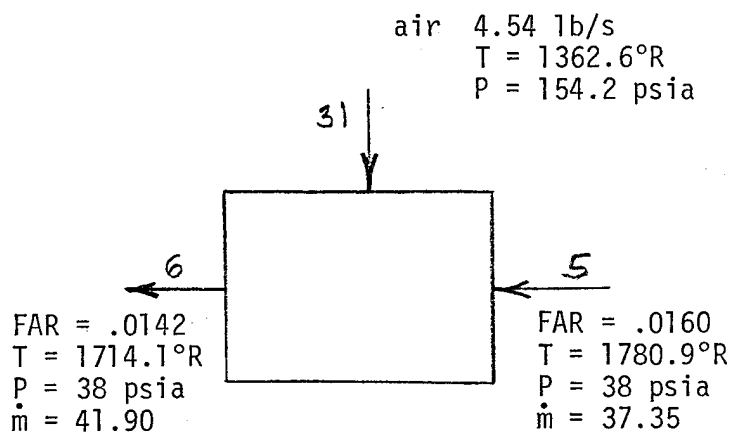
$$\dot{W} = 6177 \text{ B/s}$$

$$\dot{E}x_4 - \dot{E}x_5 - \dot{W} = \dot{E}x_D$$

$$37.35 [(617.52 - 518.7 \times 1.827) - (452.14 - 518.7 \times 1.841)] - 6177 = \dot{E}x_D$$

$$37.35 [172.64] = 6177 = \underline{\underline{271 \text{ B/s} = \dot{E}x_D}}$$

MIXER



$$(h_0 - T_0 S_0)_{31} = 123.78 - 518.7 \times 1.5910; \quad (h - T_0 S)_{31} = 332.70 - 518.7 \times 1.6676$$

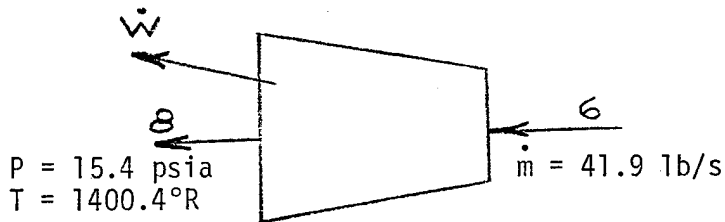
$$(h_0 - T_0 S_0)_5 = 124.75 - 518.7 \times 1.5912; \quad (h - T_0 S)_5 = 452.14 - 518.7 \times 1.841$$

$$(h_0 - T_0 S_0)_6 = 124.64 - 518.7 \times 1.5912; \quad (h - T_0 S)_6 = 432.69 - 518.7 \times 1.8297$$

$$\dot{E}x_D = 4.54 [169.2] + 37.35 [197.82] - 41.9 [184.34]$$

$$\underline{\underline{\dot{E}x_D = 433 \text{ B/s}}}$$

L.P. TURBINE



$$\dot{E}x_D = \dot{E}x_6 - \dot{E}x_8 - \dot{W}$$

$$\dot{E}x_D = 41.9 [(432.69 - 518.7 \times 1.8297) - (347.47 - 518.7 \times 1.837)] - 3571 \text{ B/s}$$

$$\dot{E}x_D = 41.9 [518.7(1.837 - 1.8297)] = \underline{\underline{158 \text{ B/s}}}$$

HEAT EXCHANGER

$$\dot{E}x_D = T_0 (\Sigma \Delta S)$$

$$= 518.7 [(1.6676 - 1.6169) 41.31 + (1.7990 - 1.837) 41.9]$$

$$\dot{E}x_D = \underline{\underline{262 \text{ B/s}}}$$

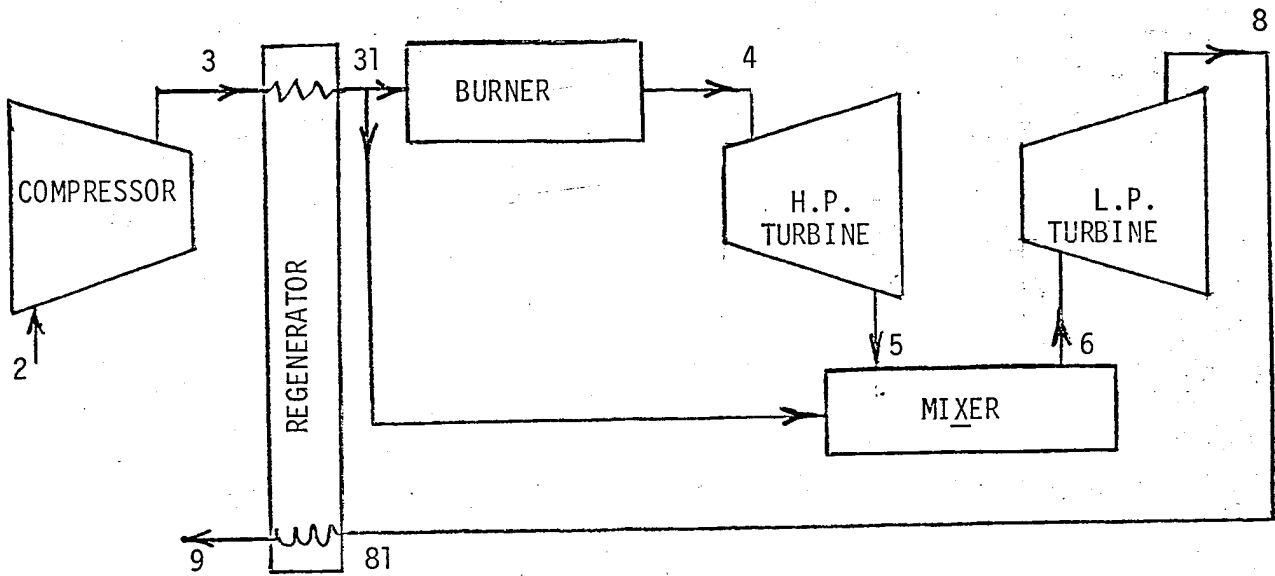
$$E x_9 = 41.9 [(293.97 - 518.7 \times 1.7990) - (124.64 - 518.7 \times 1.5912)]$$

$$\dot{E}x_9 = \underline{\underline{2579 \text{ B/s}}}$$

SUMMARY

PERCENT

		(%)	(%) not counting burner
COMPRESSOR	555	7.35	13.03
BURNER	3292	43.60	-
H.P. TURBINE	271	3.59	6.36
MIXER	433	5.73	10.17
L.P. TURBINE	158	2.09	3.71
HEAT EXCHANGER	263	3.48	6.18
EXHAUST	2579	34.15	60.55



STATION	TEMP R	PRESS PSI	ENTH BTU/LB	FAR	MASSFLOW LB/SEC	S°	$R \frac{P}{14.7}$	s
2	560.0	14.6	133.65		29.00	1.6094	0	1.6094
3	1107.6	119.4	267.53		27.55	1.7758	.1435	1.6323
31	1532.0	118.6	377.51		27.55	1.8595	.1430	1.7165
4	2414.7	113.9	633.07	.0144	27.95	1.9929	.1405	1.8524
5	1931.9	39.2	494.02	.0144	27.95	1.9287	.0673	1.8614
6	1893.8	37.6	482.87	.0137	29.40	1.9228	.0644	1.8584
8	1601.1	16.1	401.71	.0137	29.40	1.8763	.0062	1.8701
81	1601.1	15.8		.0137	29.40	1.8763	.0050	1.8713
9	1206.4	14.9	296.25	.0137	29.40	1.8009	.0009	1.8000

Compressor

$$\dot{E}_{\dot{D}} = 29(518.7)(1.6323 - 1.6094) = \underline{\underline{344 \text{ B/s}}}$$

H.P. Turbine

$$\dot{E}_{\dot{D}} = 27.95(518.7)(1.8614 - 1.8524) = \underline{\underline{130 \text{ B/s}}}$$

L.P. Turbine

$$\dot{E}_{\dot{D}} = 29.4(518.7)(1.8701 - 1.8584) = \underline{\underline{178 \text{ B/s}}}$$

HEAT EXCH

$$\dot{E}_{\dot{D}} = 518.7 [29(1.7165 - 1.6323) + 29.4 (1.8000 - 1.8713)]$$

$$\dot{E}_{\dot{D}} = \underline{\underline{179 \text{ B/s}}}$$

BURNER

$$\dot{E}_{\dot{D}} = \dot{m}_f (\text{LHV}) + \dot{m}_f (\Delta h_f - T_o S)_f + \dot{m}_a \frac{(\Delta h - T_o S)_a}{T_a - 537} - \dot{m}_p (\Delta h - T_o S)_p$$

$$\dot{m}_f (\text{LHV}) = .40 (18,400) = \underline{\underline{7360 \text{ B/s}}}$$

$$\dot{m}_f (\Delta h - T_o S)_f = .40 [(.5 \times 23) - 518.7 \times .9] = \underline{\underline{-182 \text{ B/s}}}$$

$$\Delta h_{\text{air}} = (377 - 128) = 249 \text{ B/lb}; \quad T_o S = 518.7 \times 1.7165 = 890$$

$$\dot{m}_a (\Delta h - T_o S) = 27.55 (249 - 890) = \underline{\underline{-17670 \text{ B/s}}}$$

$$\Delta h_p = (633 - 129.1) = 504 \text{ B/lb}$$

$$\dot{m}_p (\Delta h - T_o S)_p = 27.95 (504 - 518.7 \times 1.8524) = \underline{\underline{12770 \text{ B/s}}}$$

$$\dot{E}_{\dot{D}} = 7360 + (-182) + (-17670) - (-12770)$$

$$\dot{E}_{\dot{D}} = \underline{\underline{2278 \text{ B/s}}}$$

MIXER

$$\dot{E}x_{31} + \dot{E}x_5 = \dot{E}x_6 + \dot{E}x_D$$

$$1.45 [(377.5 - 518.7 \times 1.7165) - (133.65 - 518.7 \times 1.6094)] +$$

$$27.95 [(494 - 518.7 \times 1.8614) - (134.67 - 518.7 \times 1.6098)] -$$

$$29.40 [(482.9 - 518.7 \times 1.8584) - (134.62 - 518.7 \times 1.6097)] = \dot{E}x_D$$

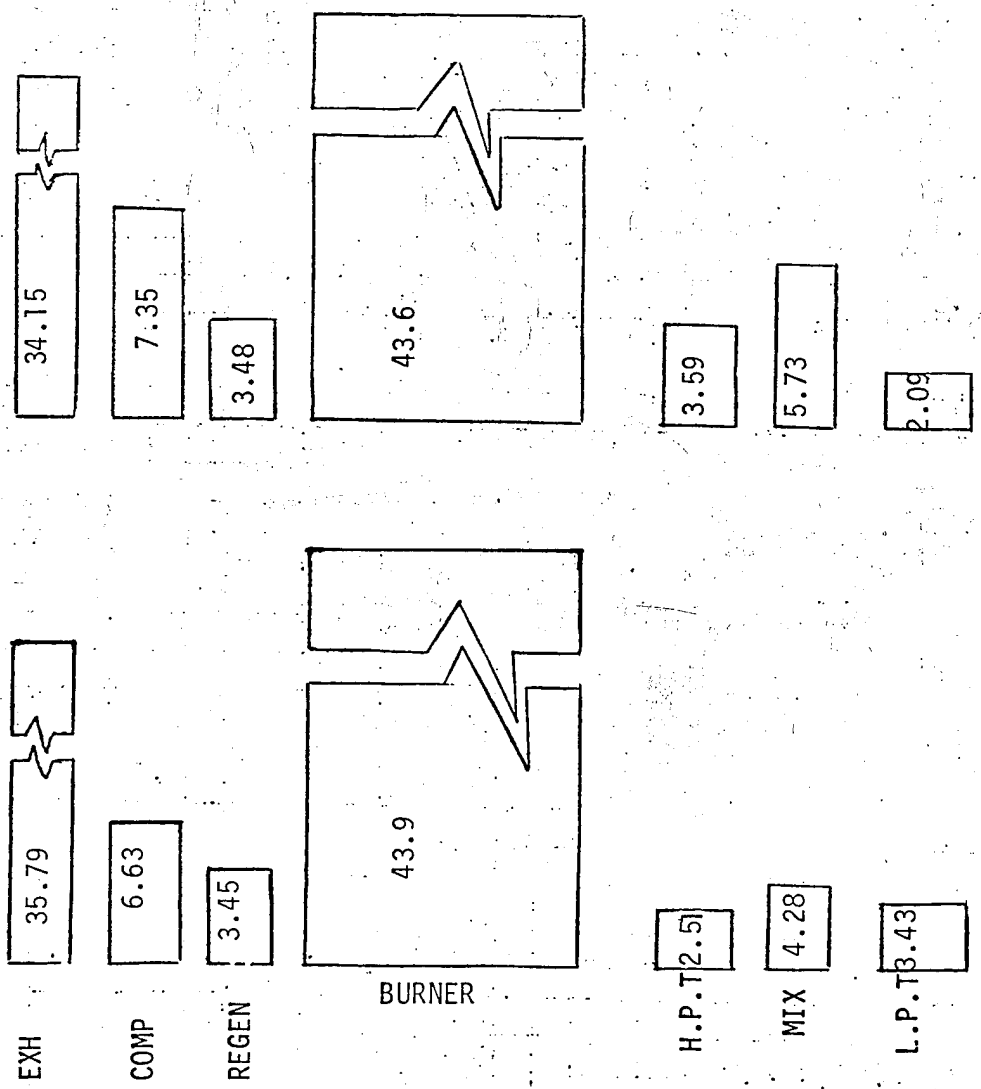
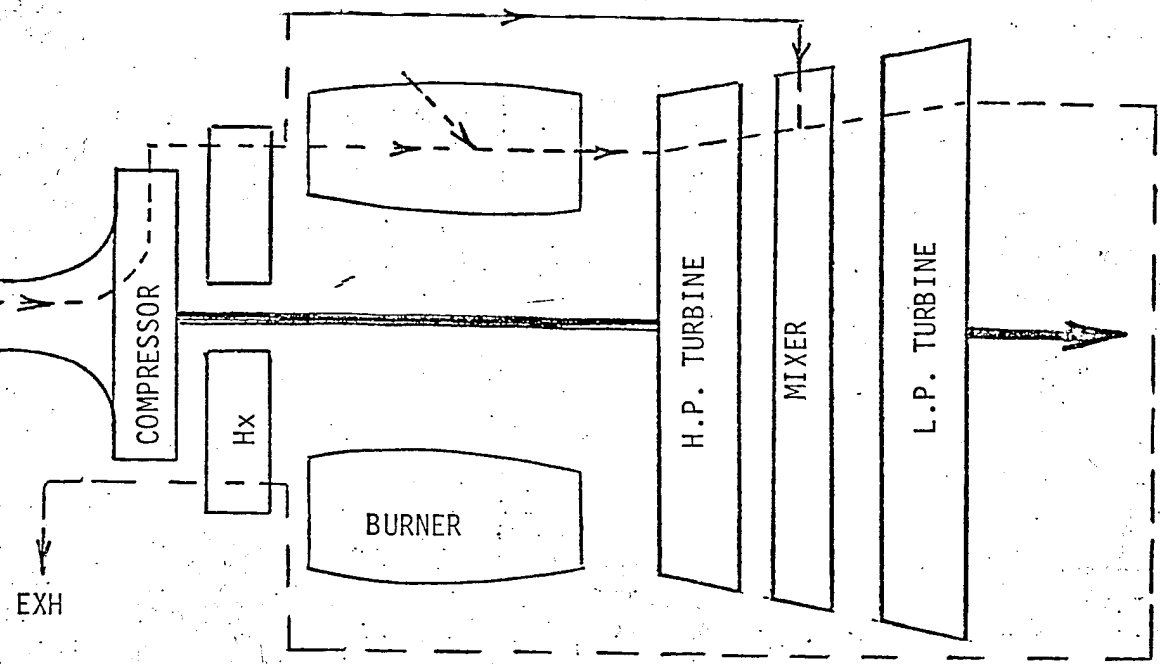
$$\dot{E}x_D = 373 + 6396 - 6447$$

$$\dot{E}x_D = \underline{222 \text{ B/s}}$$

$$\dot{E}x_9 = 29.4 [(296.5 - 518.7 \times 1.8000) - (134.62 - 518.7 \times 1.6097)]$$

$$\dot{E}x_9 = \underline{1857 \text{ B/s}}$$

	TOTAL	%
COMP.	344	6.63
BURNER	2278	43.91
H.P. TURB	130	2.51
MIXER	222	4.28
L.P. TURB	178	3.43
H.X.	179	3.45
EXH.	1857	35.79



ALL numbers are in percentage

GTF990WR<sub>86</sub>

GTF40WR<sub>86</sub>

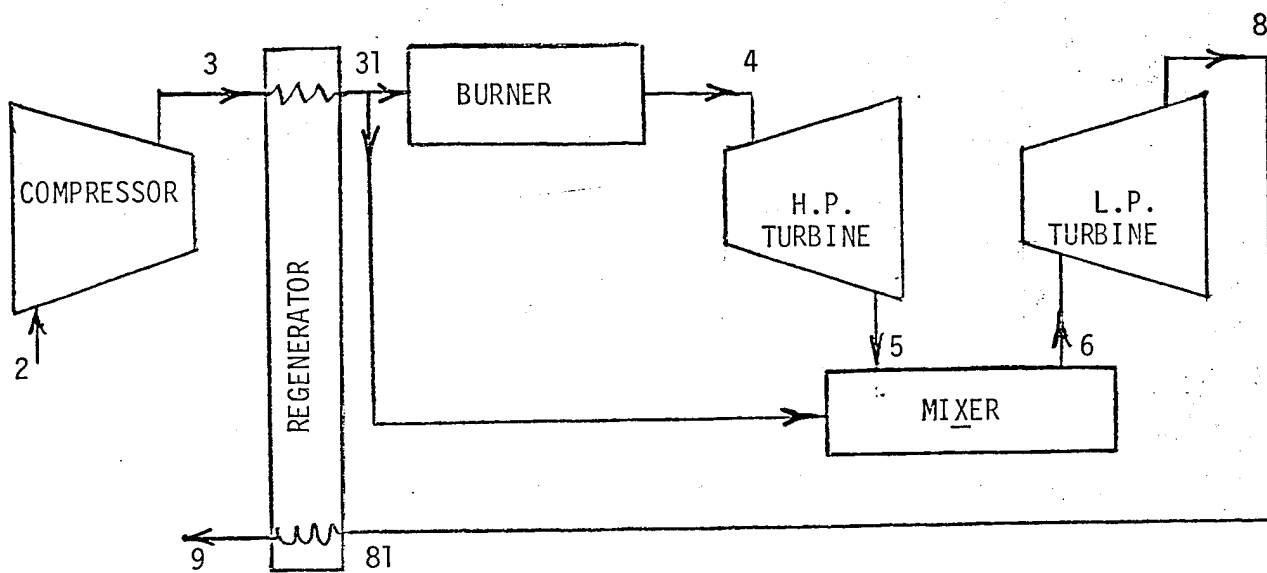
COMPARISON OF EXERGY DISSIPATION FOR GTF990WR<sub>86</sub> and GTF40WR<sub>86</sub>

APPENDIX D

CALCULATIONS AND RESULTS

GTF40WR<sub>96</sub> (LHV = 18,400 Btu/lbm)

For this calculation we will use  $T_0 = 537^\circ\text{R}$ ,  $P_0 = 14.7$  psia. The fuel will be one with a LHV = 18400. Schematic and state points are shown below.



The approach in this analysis is to determine the lost or dissipated exergy in each component rather than the absolute values of exergy.

STATION	TEMP R	PRESS PSI	ENTH BTU/LB	FAR	MASS FLOW	LB/SEC
2	560.0	14.6	133.81		29.00	
3	1107.6	119.4	267.81		27.55	
31	1580.5	118.6	390.00		27.55	
4	2414.7	113.9	532.14	.0136	27.93	
5	1930.9	39.2	492.95	.0136	27.93	
6	1892.7	37.6	481.80	.0129	29.38	
8	1600.2	16.1	400.8	.0129	29.38	
81	1600.2	15.8		.0129	29.38	
9	1432.2	14.9	279.8	.0129	29.38	

2-3 Compressor (Q = 0)

$$\dot{W} = (267.81 - 133.81) 29.0 = 3886 \text{ B/s}$$

$$\dot{E}x_2 + \dot{E}x_W = \dot{E}x_3 + \dot{E}x_D$$

$$\dot{m}[(h - T_0 S)_2 - (h_0 - T_0 S_0)] + 3886 = \dot{m}[(h - T_0 S)_3 - (h_0 - T_0 S_0)] + \dot{E}x_D$$

$$\phi_2 = 1.6094 \text{ B/lbm } ^\circ\text{R} = S_2$$

$$\phi_3 = 1.7758; \quad S_3 = 1.7758 - .068 \ln \frac{119.4}{14.7} = 1.6321$$

$$29[133.81 - 537 (1.6094)] + 3886 - 29[267.81 - 537 (1.6321)] = \dot{E}x_D$$

or

$$\dot{E}x_D = mT_0 [S_3 - S_2] = 353.5 = \underline{\underline{354 \text{ B/s}}}$$

4-5 HP TURBINE

$$\dot{W} = 27.93 [632.45 - 493.30] = 3886 \text{ B/s} \quad \begin{matrix} \text{True only} \\ \text{(if adiabatic)} \end{matrix}$$

$$\phi_4 = 1.9924; \quad S_4 = 1.9924 - .0686 \ln \frac{113.9}{14.7} = 1.8519 \text{ B/lb } ^\circ\text{R}$$

$$\phi_5 = 1.9282; \quad S_5 = 1.9282 - .0686 \ln \frac{39.2}{14.7} = 1.8609$$

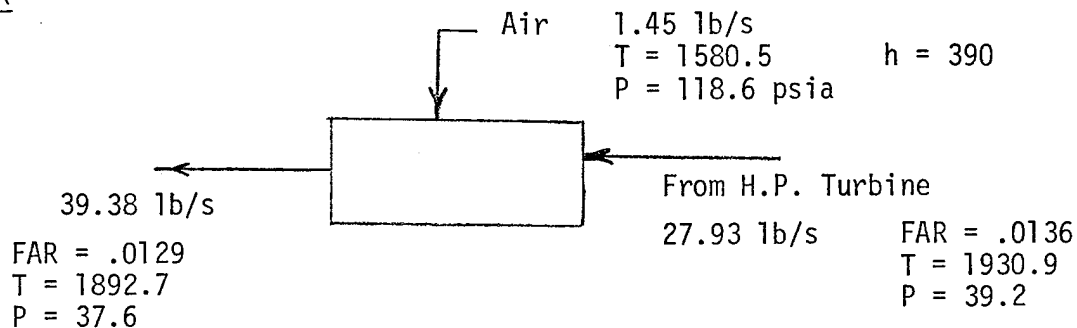
$$[(h_4 - T_0 S_4) - (h_0 - T_0 S_0)] = [(h_5 - T_0 S_5) - (h_0 - T_0 S_0)] + (h_4 - h_5) + ex_D$$

$$+ T_0(S_5 - S_4) = ex_D$$

$$537(1.8609 - 1.8519) = 4.83 \text{ B/lbm} = ex_D$$

$$\dot{Ex}_D = 4.83 \times 27.93 = 135 \text{ B/s}$$

MIXER



$$\dot{Ex}_A + \dot{Ex}_5 = \dot{Ex}_6 + \dot{Ex}_D$$

$$1.45[390.0 - 537 \times (1.8678 - .06855 \ln \frac{118.6}{14.7}) - (128.2 - 537 \times 1.5993)]$$

$$+ 27.93[492.95 - 537 \times (1.9282 - .0686 \ln \frac{39.2}{14.7}) - (129.0 - 537 \times 1.5995)]$$

$$- 29.38[481.8 - 537 \times (1.9223 - .0686 \ln \frac{37.6}{14.7}) - (129.0 - 537 \times 1.5996)]$$

$$= \dot{Ex}_D$$

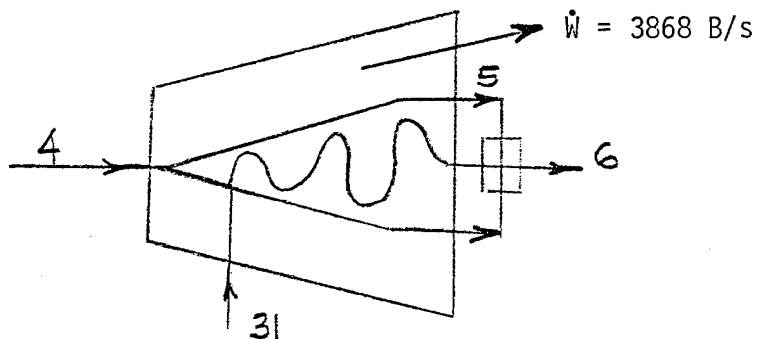
$$\dot{Ex}_D = 282 + 6244 - 6290 = \underline{\underline{236 \text{ B/s}}}$$

$$\text{H.P. Turb \& mix } \dot{Ex}_D = 135 + 236 = \underline{\underline{371 \text{ B/s}}}$$

COMPARE WITH NEXT PAGE

(alternate approach)

COMBINED TURBINE & MIXER



$$\phi_{31} = 1.8678 \quad S_{31} = 1.8678 - .0686 \ln \frac{118.6}{14.7} = 1.7246 \text{ B/lbm } ^\circ\text{R}$$

$$\phi_6 = 1.9223 \quad S_6 = 1.9223 - .0686 \ln \frac{37.6}{14.7} = 1.8579$$

Check energy balance

$$(632.45) 27.93 + (390.41)(1.45) = 3886 + (482.17)(29.38)$$

$$18230 = 18052 \approx 1\% \text{ off}$$

$$\dot{m}_4 [(h_4 - T_0 S_4) - (h_0 - T_0 S_0)] + \dot{m}_{31} [(h_{31} - T_0 S_{31}) - (h_0 - T_0 S_0)]$$

$$= \dot{W} + \dot{m}_6 [(h_6 - T_0 S_6) - (h_0 - T_0 S_0)] + \dot{E}x_D$$

Note:  $h_{fg}$  on both sides will cancel

$$27.93[(632.45 - 537 \times 1.8519) - (129 - 537 \times 1.5996)] +$$

$$1.45[(390.41 - 537 \times 1.7246) - (128.2 - 537 \times 1.5993)] - 3886$$

$$- 29.38[(482.17 - 537 \times 1.8579) - (129.00 - 537 \times 1.5997)] = \dot{E}x_D$$

$$\underline{\underline{\dot{E}x_D = 373 \text{ B/s}}}$$

## BURNER

Use  $S_{fuel} \approx 0.9 \text{ B/lbm } ^\circ\text{R}$  and let  $T_{fuel} = T_{537} = T_0$

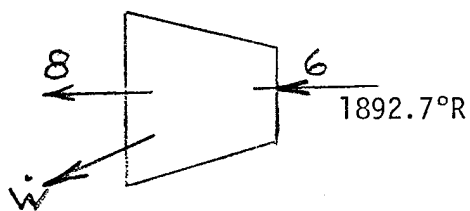
$$\dot{E}x_D = \dot{m}_f(\text{LHV}) + \dot{m}_f(\Delta h_f - T_0 S_f) + \dot{m}_{air}(\Delta h_{T_0-537} - T_0 S)_{air} \\ - \dot{m}_p(\Delta h_p - T_0 S)_p$$

$$= (.38)(18400) + .38(0 - 537 \times .9) + 27.55[(390.0 - 128.2) - 537 \times 1.7246] \\ - 27.93[(632.1 - 129.0) - 537 \times 1.8519]$$

$$\dot{E}x_D = 6992 - 184 - 18,302 + 13724$$

$$\underline{\underline{\dot{E}x_D = 2230 \text{ B/s}}}$$

## L.P. TURBINE



$$h_6 = 481.8$$

$$S_6 = 1.8579$$

$$h_8 = 400.8$$

$$S_8 = 1.8758 - .0686 \ln \frac{16.1}{14.7}$$

$$S_8 = 1.8696$$

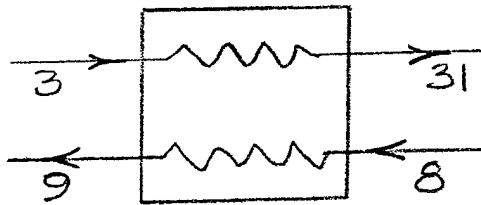
$$\dot{W} = 29.38(481.8 - 400.8) = 2379.8 \text{ B/s}$$

$$\dot{E}x_6 = \dot{E}x_8 + \dot{E}x_W + \dot{E}x_D$$

$$29.38[481.8 - 537 \times 1.8579 - (h_0 - T_0 S_0)] = 29.38[(400.8 - 537 \times 1.8696) - (h_0 - T_0 S_0)]$$

$$-\dot{W} = \dot{E}x_D \quad \therefore \dot{E}x_D = 537(1.8696 - 1.8579) 29.38 = \underline{\underline{185 \text{ B/s}}}$$

# HEAT EXCHANGER



$$\dot{E}x_3 + \dot{E}x_8 = \dot{E}x_{31} + \dot{E}x_9 + \dot{E}x_D$$

$$\dot{m}_3[(h_3 - T_0 S_3) - (h_0 - T_0 S_0)_{3-31}] + \dot{m}_8[(h_8 - T_0 S_8) - (h_0 - T_0 S_0)_{8-9}] =$$

$$\dot{m}_3[(h_{31} - T_0 S_{31}) - (h_0 - T_0 S_0)_{3-31}] + \dot{m}_8[(h_9 - T_0 S_9) - (h_0 - T_0 S_0)_{8-9}] + \dot{E}x_D$$

$$29[(267.81 - 537 \times 1.6321)] + 29.38 [(400.8 - 537 \times 1.8696)] =$$

$$29[390 - 537 \times 1.7246] + 29.38[279.8 - 537(1.7869 - .0686 \ln \frac{14.9}{14.7})] + \dot{E}x_D$$

$$-17.650 - 17721 + 15535 + 19957 = \dot{E}x_D$$

$$\underline{\underline{\dot{E}x_D = 121 \text{ B/s}}}$$

The regenerator eff =  $\frac{h_{31} - h_3}{h_{31} - h_8}$  where  $h_{31}$  = enthalpy of air at  $T_8$

$$\text{eff} = \frac{390.41 - 267.81}{395.23 - 267.81} = .96$$

$$\dot{E}x_9 = [(h_9 - T_0 S_9) - (h_0 - T_0 S_0)]\dot{m}$$

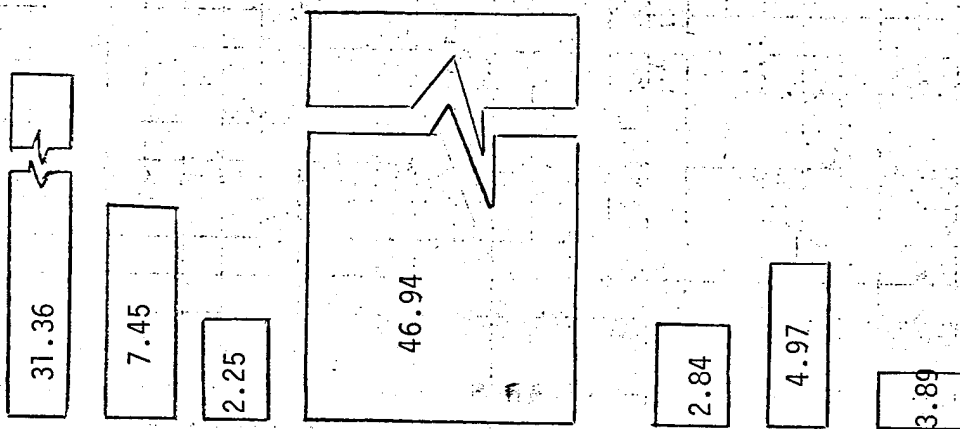
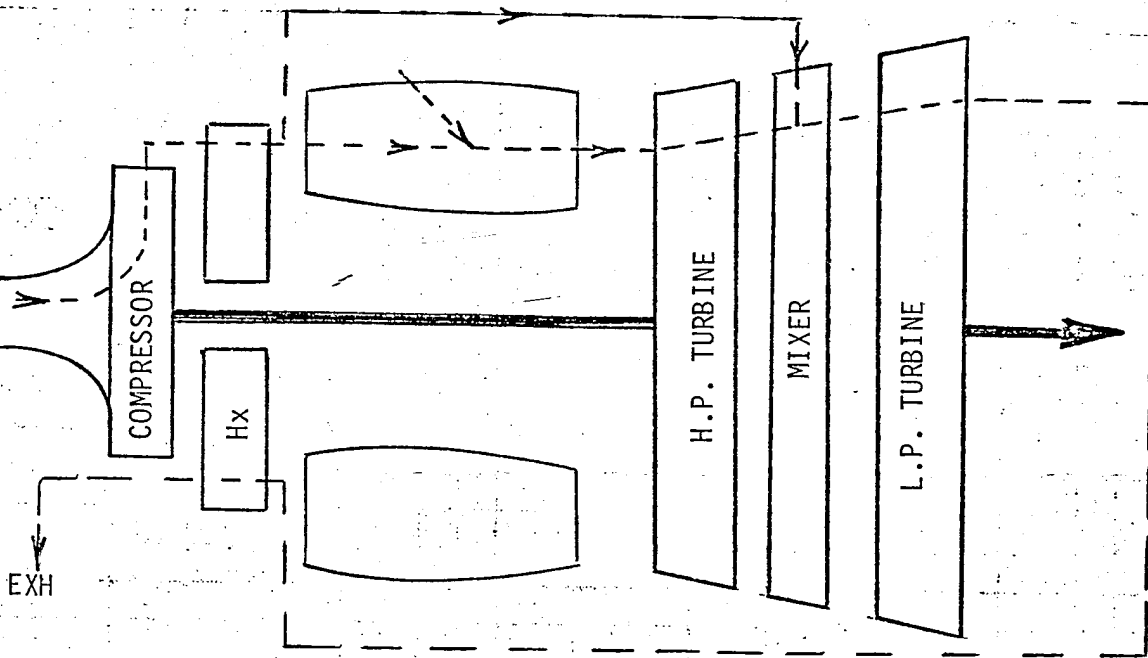
$$= 29.38[[279.8 - 537 \times (1.7869 - .0686 \ln \frac{14.9}{14.7})]$$

$$- [129 - 537 \times 1.5996]]$$

$$\dot{E}x_9 = 29.38\{[279.8 - 537 \times 1.7860] - [129 - 859]\}$$

$$\underline{\underline{\dot{E}x_9 = 1490 \text{ B/s}}}$$

<u>DISSIPATED EXERGY</u>		<u>PERCENT</u>
COMPRESSOR	354	7.45
H.P. TURBINE	135	2.84
MIXER	236	4.97
BURNER	2230	46.94
L.P. TURBINE	185	3.89
REGENERATOR	121	2.55
EXHAUST	<u>1490</u>	<u>31.36</u>
	4751	100.00



All numbers are in percentage

EXERGY DISSIPATION FOR GTF40WR96