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## ABSTRACT

A preliminary design of a coal burning 25,000 HP naval ship propulsion plant was completed. The system consists of a combined Closed Brayton cycle and bottoming Rankine cycle. Coal combustion capability is achieved by using a Pressurized Fluidized Bed (PFB) heater. A thermodynamic analysis and volume estimate was conducted for various Brayton cycle compressor pressure ratios ( $\pi_c$ ).

The results show that a maximum thermodynamic efficiency ( $\eta_r$ ) is achieved in the range of  $\pi_c = 5$  to 6. Total volume on the other hand has a minimum around  $\pi_c = 3.5$  and climbs steeply above that. A trade-off exists between efficiency and volume with a good design range of  $\pi_c = 4$  to 5. The design point was ultimately chosen at  $\pi_c = 4.5$  with a  $\eta_r = .48$ .

The design of a modern coal burning combined cycle offering high efficiency at both rated and part load is within the reach of present technology. Heat exchangers and turbo-machinery design are well within the state of the art and PFB technology is expected to come on line within the next few years.

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Preliminary Design of  
An Alternative Fuels Combined Cycle Propulsion Plant  
for Naval Ship Applications

by

Kirk Steven Burgamy

B.S. in Naval Arch., U.S. Naval Academy  
(1973)

SUBMITTED TO THE DEPARTMENT OF  
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at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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PRELIMINARY DESIGN OF AN  
ALTERNATIVES FUELS COMBINED CYCLE PROPULSION PLANT  
FOR NAVAL SHIP APPLICATIONS

by

KIRK STEVEN BURGAMY

Submitted to the Department of Ocean Engineering  
on May 1, 1981 in partial fulfillment  
of the requirements for the Degrees of Ocean  
Engineer and Master of Science in  
Mechanical Engineering

ABSTRACT

A preliminary design of a coal burning 25,000 HP naval ship propulsion plant was completed. The system consists of a combined Closed Brayton cycle and bottoming Rankine cycle. Coal combustion capability is achieved by using a Pressurized Fluidized Bed (PFB) heater. A thermodynamic analysis and volume estimate was conducted for various Brayton cycle compressor pressure ratios ( $\pi_c$ ).

The results show that a maximum thermodynamic efficiency ( $\eta_t$ ) is achieved in the range of  $\pi_c = 5$  to 6. Total volume on the other hand has a minimum around  $\pi_c = 3.5$  and climbs steeply above that. A trade-off exists between efficiency and volume with a good design range of  $\pi_c = 4$  to 5. The design point was ultimately chosen at  $\pi_c = 4.5$  with a  $\eta_t = .48$ .

The design of a modern coal burning combined cycle offering high efficiency at both rated and part load is within the reach of present technology. Heat exchangers and turbo-machinery design are well within the state of the art and PFB technology is expected to come on line within the next few years.

Thesis Supervisor: A. Douglas Carmichael

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## I. INTRODUCTION

1. Purpose. > Increasing prices and decreasing supplies of fuel oil has created a need for highly efficient ship propulsion systems capable of utilizing fuels other than oil. The purpose of this thesis is to perform a preliminary design of a combined cycle propulsion plant equipped with a multi-fuels combustor capable of burning coal or oil. ←

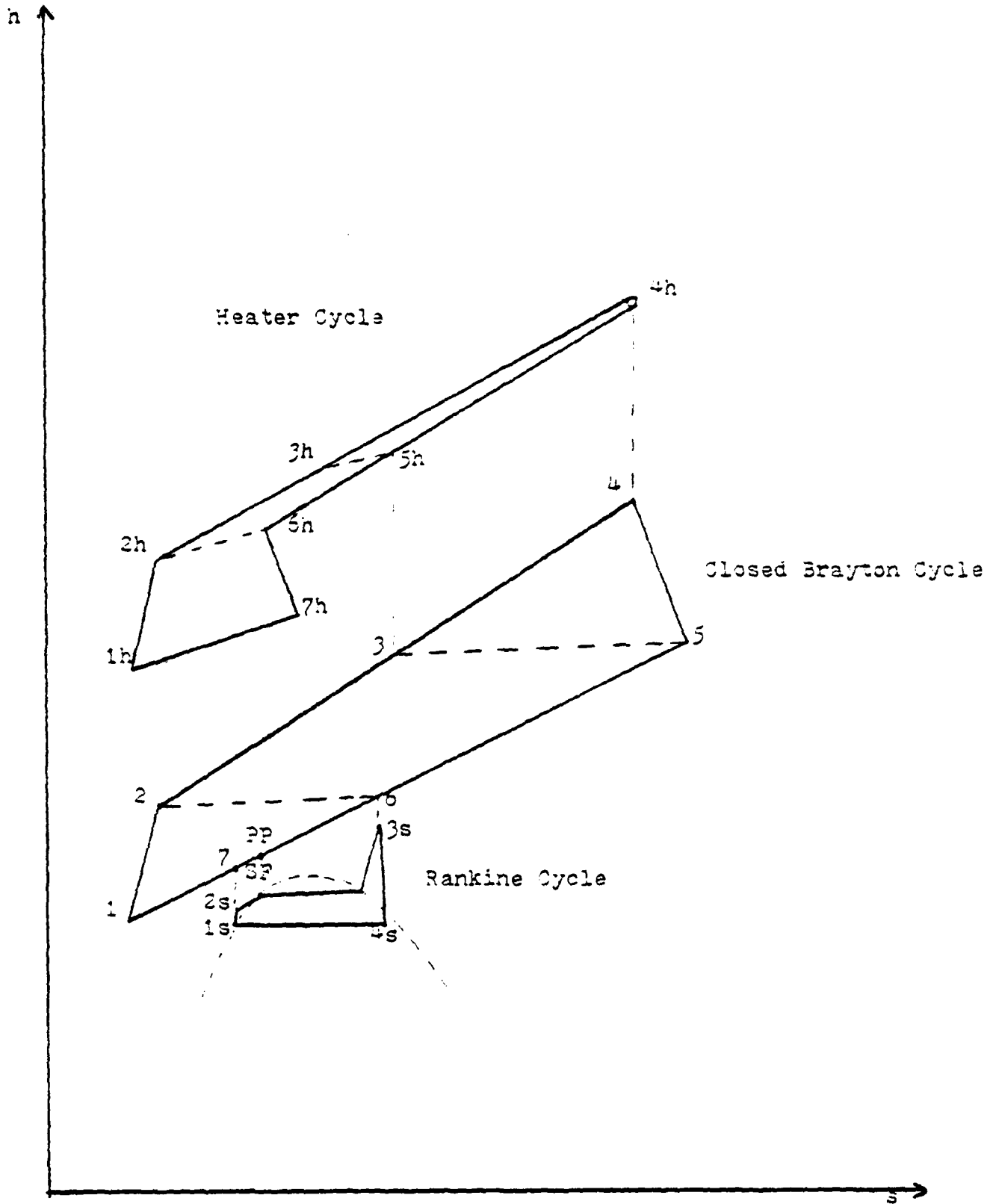
2. System Description. The system investigated is a closed regenerative Brayton Cycle combined with a bottoming Rankine cycle. Working fluids for the cycles are air and water respectively. The heater for the Brayton cycle is a pressurized fluidized bed (PFB). The heater cycle is essentially an open regenerative Brayton cycle. This thesis was conducted considering the heater only in its coal burning mode of operation. Work done by the Brayton and Rankine cycles will drive a common shaft through a double reduction type gear. An enthalpy-entropy diagram is shown on Figure 1.

3. Scope.

a. Objectives. The objectives of this thesis are to:

(1) Perform a thermodynamic analysis of the system for various closed Brayton cycle pressure ratios utilizing

Figure 1.



realistic values for component efficiencies and losses.

(2) Estimate major component volumes and thus obtain a total volume for set of parameters listed in (1) above.

(3) Select a set of parameters for design based upon the above results.

(4) Discuss the technical feasibility and implications of the design as a means for naval ship propulsion.

b. Design Criteria.

(1) The system parameters selected for design were those which gave the lowest total volume within an acceptable range of thermal efficiency.

(2) An acceptable range of thermal efficiency is defined as  $\pm 1\%$  of the maximum efficiency.

c. Limitations to Scope.

(1) No component or system testing was carried out.

(2) The system was designed with the aid of a computer utilizing performance parameters of currently available equipment.

(3) The concept of pressurized fluidized bed (PFB) combustion has not been proven in a shipboard environment. The thesis was conducted based on the assumption that a PFB system would be put to sea in the near future.

## II. THERMODYNAMIC ANALYSIS

### 1. The Brayton Cycle

a. Working cycle. This is a closed Brayton cycle utilizing air as the working fluid. Air was chosen since this is proposed for surface ship application and would thus eliminate the need for carrying a reserve supply of gas if something like Helium or  $\text{CO}_2$  were used.

Advantages of a closed cycle over an open cycle are the following:

(1) Compressor suction pressure is no longer limited to ambient. By increasing the working pressure of the cycle a significant reduction in engine size can be achieved for specified output.

(2) Higher working pressures also increases the heat transfer capacity of the working fluid thus resulting in smaller, more effective heat exchangers.

(3) The use of a high pressure fluid gives the added advantage of regulating the cycle pressure level by varying the inventory of gas in the loop. If this is done in a manner which kept the maximum temperature and speed constant, the turbomachinery vector diagrams would remain essentially unchanged. The result is little or no change in compressor or turbine efficiencies with varying load, thus maintaining high part load efficiency.

A Temperature - entropy (T-s) diagram of the working cycle is shown in Figure 2.

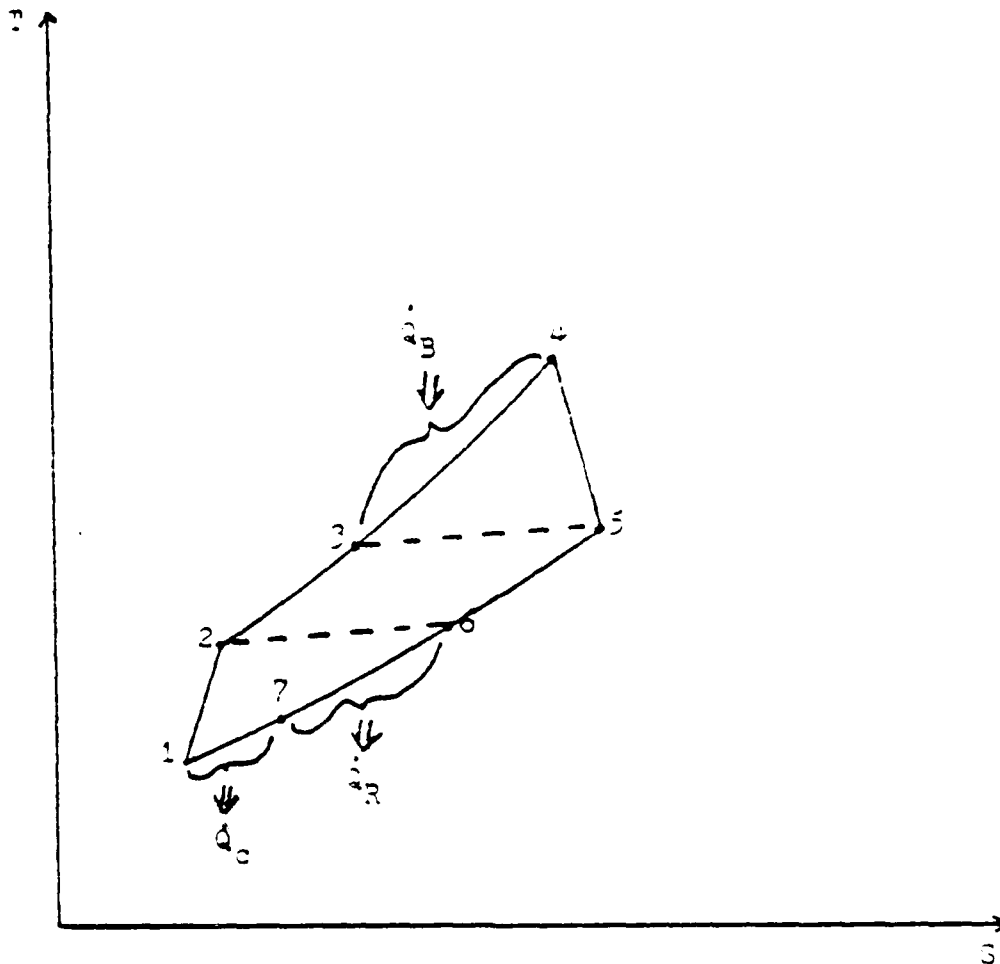


Figure 2.

- point 1: compressor suction, cooler discharge  
 2: compressor discharge, regen inlet (cold)  
 3: regen outlet (cold), heater inlet  
 4: heater outlet, turbine inlet  
 5: turbine outlet, regen inlet (hot)  
 6: regen outlet (hot), WHB inlet  
 7: WHB outlet, cooler inlet

- $\dot{Q}_H$ : heat input from heater cycle  
 $\dot{Q}_R$ : heat released to Rankine cycle  
 $\dot{Q}_C$ : heat released to sea water cooler

The analysis was conducted by assuming values for  $T_1$ ,  $T_4$ ,  $\eta_c(p)$  (compressor polytropic efficiency),  $\eta_T(p)$  (turbine polytropic efficiency),  $E_R$  (regenerator effectiveness), and  $\left(\frac{\Delta P}{P}\right)_T$  (total pressure drop).

The specific heat was assumed to vary with temperature according to the following relation:

$$C_p(T) = .2475 - (3.759 \times 10^{-5}) T + (5.106 \times 10^{-8}) T^2 - (1.231 \times 10^{-11}) T^3$$

for  $T$  in  $^{\circ}R$

$C_p$  in BTU/lbm- $^{\circ}R$

The following are defined:

- $\pi_c$  - compressor pressure ratio ( $P_2/P_1$ )
- $\pi_T$  - turbine pressure ratio ( $P_5/P_4$ )
- $\left(\frac{\Delta P}{P}\right)_T$  - % total pressure drop around closed Brayton loop
- $\dot{W}_3$  - power (net) from closed Brayton cycle
- $\dot{m}_3$  - mass flow of working fluid in Brayton cycle
- $T_i$  - temp in  $^{\circ}R$  at point  $i$
- $h_i$  - enthalpy at point  $i$
- $R$  - gas constant
- $P_i$  - pressure abs. at point  $i$
- $v$  - specific volume
- $E_R$  - regenerator effectiveness

The basic procedure was to determine  $T_2$ ,  $T_3$ ,  $T_5$ ,  $T_6$ ,  $\dot{Q}_{in}$ , and  $\dot{W}_3$  for various pressure ratios ( $\pi_c$ ).

Determination of  $T_2$  (ref. Dixon):

Small stage polytropic efficiency is

$$\eta_c(P) = \frac{dh_{is}}{dn} = \frac{v dt}{C_p dt}$$

since for an isentropic process  $T_{ds} = 0 = dh_{is} - v dp$

Substituting  $v = RT/p$  gives

$$\eta_c(P) = \frac{R}{C_p} \cdot \frac{1}{p} \cdot \frac{dp}{dt}$$

thus,

$$\int_{T_1}^{T_2} \frac{C_p}{T} dT = \frac{R}{\eta_c(P)} \int_{P_1}^{P_2} \frac{1}{p} dp = \frac{R}{\eta_c(P)} \ln \left( \frac{P_2}{P_1} \right)$$

By substituting the equation for  $C_p = C_p(T)$  one gets

$$\left. \begin{aligned} .2475 \ln \left( \frac{T_2}{T_1} \right) &= 3.759 \times 10^{-5} (T_2 - T_1) + (2.553 \times 10^{-8}) (T_2^2 - T_1^2) - \\ & (4.103 \times 10^{-12}) (T_2^3 - T_1^3) \end{aligned} \right\} \\ = \frac{R}{\eta_c(P)} \ln \pi_c$$

$T_2$  can then be determined iteratively.

Determination of  $T_5$ :

In a manner similar to the compressor above,

$$\int_{T_4}^{T_5} \frac{C_p}{T} dT = R \eta_c(P) \ln \left( \frac{P_5}{P_4} \right)$$

After integrating, this becomes

$$\begin{aligned} &.2475 \ln\left(\frac{T_5}{T_4}\right) - (3.759 \times 10^{-5})(T_5 - T_4) + (2.553 \times 10^{-8})(T_5^2 - T_4^2) - \\ &\quad (4.103 \times 10^{-12})(T_5^3 - T_4^3) \\ &= R \eta_r(p) \ln\left(\frac{T_5}{T_4}\right) \end{aligned}$$

$T_5$  can then be determined iteratively.

Determination of  $T_3$  and  $T_6$ :

$T_3$  and  $T_6$  can be found from an assumed regenerator effectiveness ( $E_R$ ) using the following relation:

$$E_R = \frac{T_5 - T_6}{T_5 - T_2} = \frac{T_3 - T_2}{T_5 - T_2}$$

b. Heater Cycle. This is an open Brayton cycle also using combustion air as the working fluid. The heater itself is a pressurized fluidized bed utilizing coal as fuel. A T-s diagram of the heater cycle is shown in Figure 3.

Major components of the cycle consist of a heater, recuperator and turbine driven compressor. The turbine is powered by exhaust gases leaving the recuperator.

The analysis was conducted by assuming values of  $T_{1h}$ ,  $T_{7h}$ ,  $\eta_c(P)$ ,  $\eta_t(P)$ , and  $\phi$  (equivalence ratio). Both the exhaust products and combustion air were assumed to be perfect gases with specific heats varying in accordance with the relation given in i.(a).

The following are defined:

$\pi_{ch}$	-	heater compressor pressure ratio ( $P_{2h}/P_{1h}$ )
$\pi_{th}$	-	heater turbine pressure ratio ( $P_{7h}/P_{6h}$ )
$\frac{(\Delta P)}{P}_{Th}$	-	% total pressure drop around heater loop
$\dot{m}_a$	-	mass flow of air in heater cycle
$\dot{m}_f$	-	mass flow of fuel in heater cycle
$(F/A)_S$	-	stoichiometric fuel - air ratio of fuel used
LHV	-	Lower Heating Value of fuel used
$T_{1h}$	-	absolute temp at point $i_h$
$h_{1h}$	-	enthalpy at point $i_h$
$\eta_H$	-	efficiency of the heater cycle
$E_{REC}$	-	recuperator effectiveness

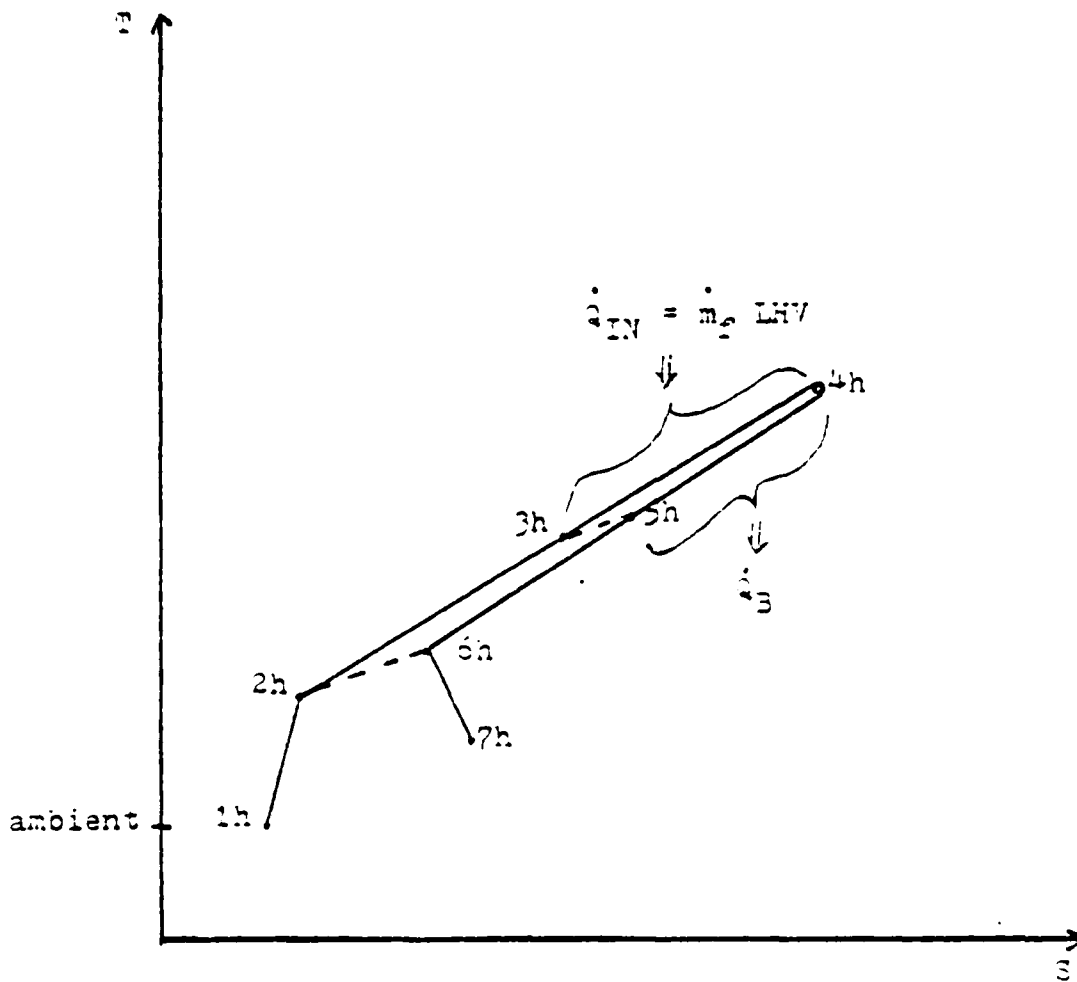


Figure 3.

- point 1h: compressor inlet
- 2h: compressor outlet, recup inlet (cold)
- 3h: recup outlet (cold), heater inlet
- 4h: max air temp in heater
- 5h: heater outlet, recup inlet (hot)
- 6h: recup outlet (hot), turbine inlet
- 7h: turbine exhaust

$q_3$ : heat released to working cycle

$q_{in}$ : heat in =  $m_f LHV$

Assume the heater cycle to be a control volume (C.V.) as shown in Figure 4.

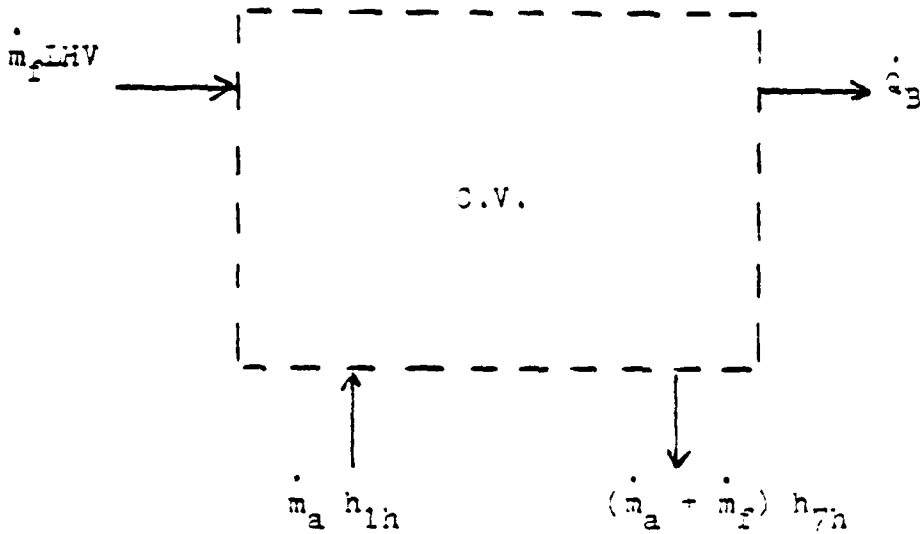


Figure 4.

$\dot{q}_2$  leaving the C.V. must be equal to  $\dot{q}_3$  entering the working cycle thus,

$$\dot{q}_3 = \dot{m}_3 (h_{4h} - h_3) = (\dot{m}_a + \dot{m}_f) (h_{4h} - h_{5h})$$

Performing a heat balance on the C.V. gives us

$$\dot{q}_3 + (\dot{m}_a + \dot{m}_f) h_{7h} = \dot{m}_f \text{LHV} + \dot{m}_a h_{1h}.$$

Therefore,

$$\eta_f \equiv \frac{\dot{q}_3}{\dot{q}_{in}} = \frac{\dot{q}_3}{\dot{m}_f \text{LHV}} = 1 - \frac{[(1 + (F/A)_s \phi) h_{7h} - h_{1h}]}{[(F/A)_s \phi \text{LHV}]}$$

Assume the heater cycle to be a control volume (C.V.) as shown in Figure 4.

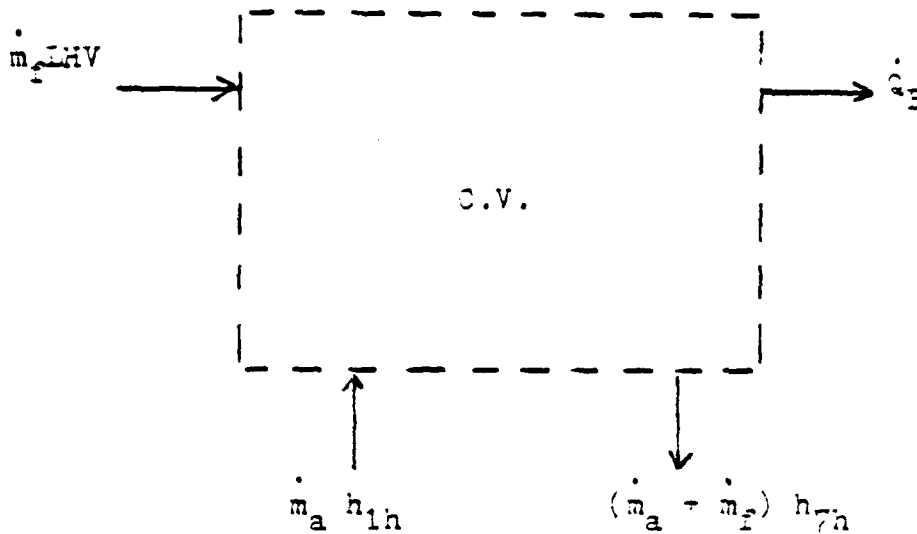


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Performing a heat balance on the C.V. gives us

$$\dot{Q}_3 + (\dot{m}_a + \dot{m}_f) h_{7h} = \dot{m}_f \text{LHV} + \dot{m}_a h_{1h}.$$

Therefore,

$$\eta_f \equiv \frac{\dot{Q}_3}{\dot{Q}_{in}} = \frac{\dot{Q}_3}{\dot{m}_f \text{LHV}} = 1 - \frac{[(1 + (F/A)_s \phi) h_{7h} - h_{1h}]}{[(F/A)_s \phi \text{LHV}]}$$

From a power balance between the turbine and compressor

$$\dot{W}_c = \dot{W}_T \text{ (no net work)}$$

$$\dot{m}_a \bar{C}_{pc} (T_{h2} - T_{h1}) = (\dot{m}_a + \dot{m}_f) \bar{C}_{pt} (T_{6h} - T_{7h})$$

but

$$T_{2h} = T_{1h} (\pi_{ch})^{C_{pc}/\gamma_c(p)}$$

$$T_{6h} = T_{7h} (\pi_{th})^{C_{pt}/\gamma_t(p)}$$

$$\pi_{th} = \left( \left[ 1 - \frac{\Delta P}{P} \right]_{th} \pi_{ch} \right)^{-1}$$

thus,

$$\bar{C}_{pc} T_{1h} \left[ (\pi_{ch})^{C_{pc}/\gamma_c(p)} - 1 \right] = \left[ 1 + (F/A)_s \phi \right] \bar{C}_{pt} T_{7h} \left[ (\pi_{th})^{C_{pt}/\gamma_t} - 1 \right]$$

$$= \left[ 1 + (F/A)_s \phi \right] \bar{C}_{pt} T_{7h} \left\{ \left[ 1 - \frac{\Delta P}{P} \right]_{th}^{C_{pt}/\gamma_t} \left[ \frac{T_{1h}}{T_{2h}} \right]^{C_{pt}/\gamma_t} - 1 \right\}$$

or,

$$\bar{C}_{pc} T_{1h} \left[ (\pi_{ch})^{C_{pc}/\gamma_c} - 1 \right] + \left[ 1 + (F/A)_s \phi \right] \bar{C}_{pt} T_{7h} =$$

$$\left[ 1 + (F/A)_s \phi \right] \bar{C}_{pt} T_{7h} \left[ 1 - \left( \frac{\Delta P}{P} \right)_{th} \right]^{C_{pt}/\gamma_t} \pi_c^{C_{pt}/\gamma_t}$$

therefore,

$$\left[ 1 - \left( \frac{\Delta P}{P} \right)_{Th} \right]^{C_p \eta_t} = \frac{\bar{C}_{pc} T_{th} [(\pi_{ch})^{C_p/\eta_c} - 1] + [1 + (\bar{F}/A)_s \rho] \bar{C}_{p+} T_{th}}{[1 + (\bar{F}/A)_s \rho] \bar{C}_{p+} T_{th} (\pi_{ch})^{C_p \eta_t}}$$

For minimum volume heat exchangers we want the largest

$\left( \frac{\Delta P}{P} \right)_{Th}$  compatible with the above eqn.

differentiating,

$$C_p \eta_t \left[ 1 - \left( \frac{\Delta P}{P} \right)_{Th} \right]^{C_p \eta_t - 1} \left( \frac{-d \left( \frac{\Delta P}{P} \right)_{Th}}{d \pi_{ch}} \right) =$$

$$\frac{\left\{ [1 + (\bar{F}/A)_s \rho] \bar{C}_{p+} T_{th} (\pi_{ch})^{C_p \eta_t} \bar{C}_{pc} T_{th} \bar{C}_{pc} / \eta_c (\pi_{ch})^{C_p/\eta_c - 1} \right\} - \left\{ [1 + (\bar{F}/A)_s \rho] \bar{C}_{p+} T_{th} \bar{C}_{p+} \eta_t (\pi_{ch})^{C_p \eta_t - 1} \bar{C}_{pc} T_{th} (\bar{C}_{pc} T_{th} [(\pi_{ch})^{C_p/\eta_c} - 1] + [1 + (\bar{F}/A)_s \rho] \bar{C}_{p+} T_{th}) \right\}}{\left\{ [1 + (\bar{F}/A)_s \rho] \bar{C}_{p+} T_{th} (\pi_{ch})^{C_p \eta_t} \right\}^2}$$

Setting  $\frac{\left( \frac{\Delta P}{P} \right)_{Th}}{\pi_{ch}} = 0$  and solving for  $\pi_{ch}$  gives

$$\pi_{ch} = \left\{ \frac{[1 + (\bar{F}/A)_s \rho] \bar{C}_{p+} \eta_t (\bar{C}_{p+} T_{th} - \bar{C}_{pc} T_{th})}{\bar{C}_{pc} T_{th} (\bar{C}_{pc} / \eta_c - \bar{C}_{p+} \eta_t)} \right\} \eta_c / C_p$$

By substitution

$$\left(\frac{\Delta P}{P}\right)_{Th} = 1 - \left\{ \frac{[1 + (\bar{F}/A)_s \rho] \bar{C}_{p4} T_{3h} + \bar{C}_{p2} T_{1h} [(\pi_{ch})^{c_p/m_c} - 1]}{[1 + (\bar{F}/A)_s \rho] \bar{C}_{p4} T_{3h} (\pi_{ch})^{c_p/\rho_4}} \right\} \frac{1}{c_p/\rho_4}$$

Thus  $\pi_{ch}$  and  $\left(\frac{\Delta P}{P}\right)_{Th}$  can be found through known or assumed quantities.

Determination of  $T_{3h}$ ,  $T_{5h}$

$$\epsilon_{rec} \equiv \frac{C_n (T_{3h} - T_{6h})}{C_{min} (T_{3h} - T_{2h})} = \frac{C_c (T_{3h} - T_{2h})}{C_{min} (T_{3h} - T_{2h})}$$

where  $C_n = \bar{C}_{p4} (\dot{m}_a + \dot{m}_f)$

$$C_c = \bar{C}_{p2} \dot{m}_a$$

therefore,

$$T_{3h} = T_{2h} + [1 + (\bar{F}/A)_s \rho] (T_{3h} - T_{6h})$$

$T_{2h}$  and  $T_{6h}$  can be found once  $\pi_{ch}$  is determined. Assume that

$$T_{5h} = T_3 + 100^\circ R$$

2. The Rankine Cycle. This is a bottoming steam cycle that recovers heat from the closed Brayton cycle that would otherwise be discharged overboard through the cooler. The relatively hot gas leaving the regenerator is pre-cooled in the Waste Heat Boiler (WHB) before being sent to the cooler which brings the temperature down to compressor inlet conditions. A T-s diagram of the Rankine cycle is shown in Figure 5.

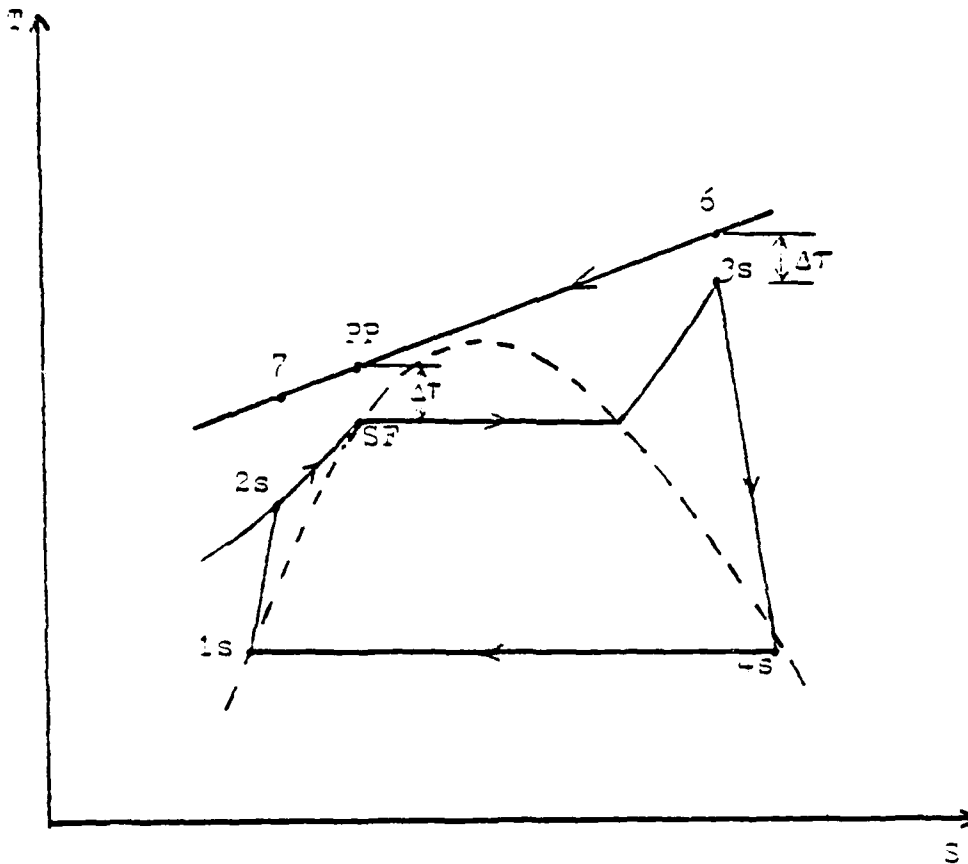


Figure 5.

Major components of the cycle are the WHB, condenser, steam turbine, and feed pump. It is assumed that the feed pump is driven with power from the turbine.

The analysis was conducted by assuming values of  $T_{1s}$ ,  $\Delta T$ ,  $\eta_{p(is)}$  (pump isentropic efficiency),  $\eta_{t(is)}$  (turbine isentropic efficiency), and  $\eta_{WHB}$  (waste heat boiler efficiency).

The following are defined:

- $h_{1s}$  - enthalpy at point 1s
- $T_{1s}$  - absolute temp at point 1s
- PP - pinch point on Brayton side
- SF - saturation point on steam side
- $\beta$  - mass flow ratio ( $\dot{m}_3/\dot{m}_2$ )
- x - quality of steam exiting turbine
- $P_{1s}$  - absolute pressure at point 1s
- $\dot{w}_R$  - power (net) from the steam cycle
- $\eta_T$  - thermal efficiency of the combined cycle
- $\dot{m}_S$  - mass flow of steam in Rankine cycle

Rankine cycle parameters were chosen for maximum work.

The procedure was as follows:

- (1) Compute  $T_{3S}$  from the relation

$$T_{3S} = T_6 - \Delta T$$

- (2) Assume a value for  $T_{pp}$ .  $T_1 < T_{pp} < 662.0^\circ F$

- (3) Compute  $T_{SF}$  from the relation

$$T_{SF} = T_{PP} - \Delta T$$

- (4) Obtain  $P_{SAT}$ ,  $h_{SF}$ ,  $h_{3S}$  from steam tables.

- (5) Compute  $h_{4S}$  from the relation

$$h_{4S} = h_{3S} - \eta_t(is)(h_{3S} - h_{4S}(is)) \quad \text{get } h_{4S}(is) \text{ from steam table}$$

- (6) Obtain  $x$  (turbine exit),  $h_{2S}$  from steam tables

- (7) Compute  $h_{2S}$  from the relation

$$h_{2S} = h_{1S} + \frac{h_{2S}(is) - h_{1S}}{\eta_P(is)}$$

- (8) Compute  $\beta$  from the relation

$$\beta = \frac{\dot{m}_4}{\dot{m}_3} = \frac{\eta_{AMB} (h_6 - h_{PP})}{h_{3S} - h_{SF}}$$

- (9) Compute  $\dot{W}_R$  from the relation

$$\dot{W}_R = \dot{m}_3 \beta [(h_{3S} - h_{4S}) - (h_{2S} - h_{1S})]$$

- \*(10) Iterate with  $T_{PP}$  (step 2) until  $\dot{W}_R$  is maximum.

- (11) Compute  $T_7$  from the relation

$$C_p(T_7) \cdot T_7 = C_p(T_{PP}) \cdot T_{PP} - \beta (h_{SF} - h_{2S}) / \eta_{AMB}$$

- (12) Calculate  $\eta_t$  from the relation

$$\eta_t = \frac{\dot{W}_B + \dot{W}_R}{\dot{Q}_B}$$

### III. VOLUME ANALYSIS

i. Turbomachinery. An analytical procedure for the minimum volume design of turbomachinery was developed by Lee (ref. 10). The following equations and mathematical expressions summarize that portion of the procedure which are applicable to compressor and turbine designs in this thesis. Volume obtained by Lee's method neglects the volume of casing, inlet and outlet plenums, and bearing assemblies.

a. Turbine. Free vortex blading and axial exit stages were assumed throughout the analysis.

The following are defined:

S.F.	-	factor of safety
$U_t$	-	max. allowable tip speed
$\phi_t$	-	flow coefficient at tip
$\psi_a$	-	hub-tip ratio at inlet
$\psi_s$	-	hub-tip ratio at exit
$C_L$	-	clearance factor
$V_a$	-	specific volume at inlet
$r_t$	-	max tip radius
$n$	-	polytropic coefficient
$K$	-	isentropic exponent
$\rho_m$	-	density of blade material
$\alpha$	-	stress concentration factor at root
$a$	-	amplification factor
$\theta$	-	correction factor for taper

$x_1$  - dist. from tip to 1st principle axis  
          chord

$K_{11}$  - normalized moment of inertia

$Vol_t$  - volume of turbine

The volume was computed by assuming values for SF,  $U_t$ ,  $\theta_t$ ,  
 $\gamma_a$ ,  $C_1$ , K,  $\rho_m$ ,  $\alpha$ ,  $a$ ,  $x_1$ ,  $K_{11}$ , and  $\theta$ .

$r_t$ ,  $n$ , and  $\gamma_b$  are computed from the following relations:

$$r_t = \left( m_3 \gamma_a / [C_1 U_t T (1 - \gamma_a^2)] \right)^{1/2}$$

$$n = \frac{K}{K - (K-1) \rho}$$

$$\gamma_b = \left[ 1 - \frac{r_t}{U_t} (1 - \gamma_a^2)^{-1/2} \right]^{1/2}$$

Compute  $C_1$ ,  $C_2$ ,  $C_3$ ,  $C_4$  from the following:

$$C_1 = 3.2 (1 + \gamma) \gamma_a^{-1} (1 - \gamma_a^2) U_t^2 r_t^2 K_{11} / K_{11}$$

$$C_2 = 2 (A - B r) / (SF \cdot \alpha)$$

$$C_3 = 2 B T \alpha (1 - \gamma_a^2)^{n-1} / (SF \cdot \alpha)$$

$$C_4 = - \rho_m U_t^2 / 2$$

where A and B are material dependent constants. The following  
can then be calculated:

$$N = C_1 [(1 - \gamma) / (1 - \gamma_b)] [U_t^2 - \gamma^2]$$

$$D = C_2 + C_3(1 - \gamma^2)^{-1/2} + C_4(1 - \gamma^2)$$

$$DN = C_1[-(2\gamma^2 + \gamma^4)(1 - \gamma^2) - 2\gamma(1 - \gamma^2)(1 - \gamma^2)^{-1/2} - \gamma(2\gamma^2 - 1)^2]$$

$$DD = 2\gamma(1 - \gamma^2)^{-3/2}(1 - \gamma^2)C_3 - 2\gamma C_4$$

The axial chord for a stage is given by  $b_u$ . For a large number of stages, summation of  $b_u$  for the whole turbine can be approximated by an integral:

$$\bar{I}_T = \int_{\gamma_2}^{\gamma_3} d(b_h) = \int_{\gamma_2}^{\gamma_3} d b_h$$

where

$$d(b_h) = \frac{1}{2} \left( \frac{N}{D} \right)^{-1/2} \left[ (DN \cdot D - DD \cdot N) / D^2 \right] d\gamma$$

This integral can be evaluated numerically thus,

$$V_{01T} = 2\pi r_t^2 C_L \bar{I}_T$$

b. Compressor. An approach similar to that of the turbine was used for the axial compressor. Axial exit stages were assumed in the analysis.

The volume was computed by assuming values for SF,  $U_t$ ,  $\phi_t$ ,  $\gamma_2$ ,  $C_L$ , K,  $\rho_m$ ,  $\alpha$ , a,  $x_2$ ,  $K_{I1}$ ,  $\theta$ , and  $\tau_y$  (blade material yield stress).

$r_1$ ,  $n$ , and  $\nu_3$  are computed from the following relations:

$$r_1 = \left( \dot{m}_3 \sqrt{x} \left[ \rho_r^2 d_r \pi (1 - \lambda^2) \right] \right)^{1/2}$$

$$n = \frac{K}{K - (K-1) / (\rho_c / \rho)}$$

$$\nu_3 = \left[ 1 - \pi_c^{-1/n} (1 - \lambda^2) \right]^{1/2}$$

Compute  $C_1$ ,  $C_2$ , and  $C_3$  from the following:

$$C_1 = .2 \rho_r (1 - \lambda^2) (1 - \lambda^2) d_r^2 r_1^2 \rho_r^2 \lambda_1 / K_2$$

$$C_2 = -\Theta \rho_r d_r^2 / 2$$

$$C_3 = 2 \overline{\tau}_y / (x - s^2)$$

Then calculate the following:

$$N = C_1 \left[ \frac{(1-\nu)}{(1+\nu)} \right] \left[ \frac{(\rho_r^2 - .49 \nu^2)}{(\rho_r^2 + .7225 \nu^2)} \right]$$

$$D = C_3 + C_2 (1 - \nu^2)$$

$$\begin{aligned} DN = C_1 & \left[ -(\rho_r^2 + .49 \nu^2) / (\rho_r^2 + .7225 \nu^2) (1 - \nu)^{-1} \right. \\ & - (1 - \nu) (1 + \nu)^{-2} (\rho_r^2 - .49 \nu^2) / (\rho_r^2 + .7225 \nu^2) \\ & + .93 \nu (1 - \nu) (1 + \nu)^{-1} / (\rho_r^2 + .7225 \nu^2) \\ & \left. - 1.445 (1 - \nu) (1 + \nu)^{-1} (\rho_r^2 - .49 \nu^2) (\rho_r^2 + .7225 \nu^2)^{-2} \right] \end{aligned}$$

$$DD = -2 C_2 \nu$$

As with the turbine define

$$I_T = \int_{\alpha}^{\beta} \alpha_{\text{oh}} d\alpha$$

where

$$\alpha_{\text{oh}} = \frac{1}{2} \left( \frac{V}{D} \right)^{1/2} \left[ (D_N \cdot D - DD \cdot N) D^2 \right]^{1/2}$$

This integral can be evaluated numerically thus

$$\text{Vol}_c = 2\pi r_c^2 C_L I_T$$

2. Heat Exchangers. The volumes of the Regenerator, Recuperator, Cooler, and Heater were computed using the method of minimum volume design developed by Lee (ref. 10). In essence Lee found that the optimal diameter ratio ( $D_N/D$ ) for these heat exchangers can be established as a simple relation to the pressure ratio ( $\pi_c$ ) of the cycle. The results of the optimally distributed pressure drops ( $\frac{\Delta P}{P}$ ) as reported by Lee were also studied. Parametric equations relating pressure drop to pressure ratio were developed and used in this analysis. No consideration has been made on computing the volume of the shell, headers, or other appendages. Lee's relations were developed from basic heat transfer and pressure drop relationships.

a. Regenerator. The regenerator is assumed to be a counter flow shell and tube heat exchanger. High pressure is inside the tubes as is the case for current design practices.

The following are defined:

- $\left(\frac{\Delta P}{P}\right)_{Reg}$  - % pressure drop across the regenerator (both steams)
- $\left(\frac{D_h}{D}\right)_{Reg}$  - diameter ratio for regenerator
- $\Delta h_{Reg}$  - enthalphy difference across the interior stream of Reg.
- D - tube inside diameter
- $\overline{\Delta T}$  - log mean temp. difference of hot and cold streams
- $P_r$  - Prandlt number
- $\rho$  - density
- $\mu$  - dynamic viscosity
- k - thermal conductivity

Values for  $\left(\frac{\Delta P}{P}\right)_{Reg}$  and  $\left(\frac{D_h}{D}\right)_{Reg}$  can be estimated from the following relations:

$$\left(\frac{\Delta P}{P}\right)_{Reg} = .135 - .0234 \pi_c \quad (\text{for } \left(\frac{\Delta P}{P}\right)_T = .1, \epsilon_R = .88)$$

$$\left(\frac{D_h}{D}\right)_{Reg} = .557 + .0933 \pi_c$$

Subscript 1 refers to quantities inside the tubes  
 whereas subscript 2 refers to quantities outside the tubes.  
 $A_{Reg}$  can be computed as follows:

$$A_{Reg} = \left(\frac{\pi}{4}\right) \gamma_R \gamma_c \dot{m}_G \Delta h_{rec}^{0.41} \left[1 - \left(\frac{D_1}{D_2}\right)^2\right]^{2.41} \left[\frac{1}{1 - \left(\frac{D_1}{D_2}\right)^2}\right]^{0.41}$$

where

$$\gamma = 17.24 \times \left(\frac{D_1}{D_2}\right)^{0.23} \left(\frac{D_1}{D_2}\right)^{-0.41}$$

$$\gamma = \frac{D_1^{0.23}}{D_2^{0.41}}$$

The volume can then be computed as follows:

$$Vol_{Reg} = A_{Reg} \frac{(\Delta P)_{Reg}^{-0.41}}{(\rho)_{Reg}}$$

b. Recuperator. The recuperator is similar in design to the regenerator only it refers to the heater cycle.

The following are defined:

- $\left(\frac{\Delta P}{P}\right)_{Rec}$  - % pressure drop across the recuperator (both streams)
- $\left(\frac{D_1}{D_2}\right)_{Rec}$  - diameter ratio for recuperator
- $\left(\frac{\Delta P}{P}\right)_{out_2}$  - % pressure drop across the heater side (outside tubes)
- $\left(\frac{\Delta P}{P}\right)_{PFB}$  - % pressure drop across the PFB
- $\Delta h_{Rec}$  - Enthalpy difference across the interior stream of recup.

Values for  $\left(\frac{\Delta P}{P}\right)_{Rec}$  and  $\left(\frac{D_h}{D}\right)_{Rec}$  can be estimated from the following relations

$$\left(\frac{\Delta P}{P}\right)_{Rec} = \left(\frac{\Delta P}{P}\right)_{T_1} - \left(\frac{\Delta P}{P}\right)_{T_2} - \left(\frac{\Delta P}{P}\right)_{PF3}$$

$$\left(\frac{D_h}{D}\right)_{Rec} = .65$$

Subscripts 1 and 2 refer to quantities inside and outside the tubes respectively.  $A_{Rec}$  is computed as follows:

$$A_{Rec} = \left(\frac{\pi}{4}\right) T Y m_{in} \Delta h_{in}^{-0.41} \left[ 1 + \left(\frac{D_h}{D}\right)_{Rec}^{-0.41} \right] \left[ 1 - \left(\frac{D_h}{D}\right)_{Rec}^{-0.41} \right]$$

where  $T$  and  $Y$  are as previously defined.

Then compute the volume

$$Vol_{Rec} = A_{Rec} \left(\frac{\Delta P}{P}\right)_{Rec}^{-0.41}$$

c. Cooler. The cooler is assumed to be a shell and tube heat exchanger with the gas inside the tubes and salt water outside.

The following are defined:

- $\left(\frac{\Delta P}{P}\right)_{Clr}$  - % pressure drop across the cooler (air side)
- $\left(\frac{D_h}{D}\right)_{Clr}$  - diameter ratio for cooler
- $\Delta h_{Clr}$  - enthalpy difference across the interior stream of cooler
- $V_{WHB_2}$  - sp. vol. of working fluid at WHB exit

- $\left(\frac{\Delta P}{P}\right)_{NHB}$  - % pressure drop across the NHB (air side)
- $\left(\frac{\Delta P}{P}\right)_{HT}$  - % pressure drop across the heater (inside tubes)
- $\gamma_p(P)$  - polytropic cooling water pump efficiency
- $V_H$  - sp. vol. of cooling water

Values for  $\left(\frac{\Delta P}{P}\right)_{CLR}$  and  $\left(\frac{D_h}{D}\right)_{CLR}$  are estimated from the following relations:

$$\left(\frac{\Delta P}{P}\right)_{CLR} = \left(\frac{\Delta P}{P}\right)_T + \left(\frac{\Delta P}{P}\right)_{NHB} + \left(\frac{\Delta P}{P}\right)_{R23} + \left(\frac{\Delta P}{P}\right)_{HT}$$

$$\left(\frac{D_h}{D}\right)_{CLR} = .092 \overline{T_c} + .076$$

Subscripts 1 and 2 refer to quantities inside and outside the tubes respectively.  $A_{CLR}$  is computed as follows:

$$A_{CLR} = \left(\frac{\pi}{4}\right) \overline{T_c} \gamma_c \dot{m}_s \Delta h_{CL}^{-0.5} \left[ 1 - \left(\frac{D_h}{D}\right)_{CLR} \right] \left[ 1 + \alpha \left(\frac{D_h}{D}\right)_{CLR} \right]^{1.4} \left[ 1 + C \beta \left(\frac{D_h}{D}\right)_{CLR} \right]^{1.4}$$

where  $\alpha$ ,  $\beta$ ,  $\gamma$  are as previously defined and

$$\beta = \left(\frac{\dot{m}_1}{\dot{m}_2}\right)^{-0.75} \left(\frac{u_1}{u_2}\right)^{-0.25} \left(\frac{P_1}{P_2}\right) \left(\frac{P_1}{P_2}\right)$$

$$C = \left(\frac{\dot{m}_2}{\dot{m}_1}\right) \left(\gamma_1(P) \gamma_2(P)\right)^{-1} \left(\frac{V_{W1}}{V_{W2}}\right) \left(\frac{P_2}{P_1}\right)$$

$$\alpha = \left(\frac{u_1}{u_2}\right) \left(\frac{u_1}{u_2}\right)^{-0.3} \left(\frac{\dot{m}_1}{\dot{m}_2}\right)^{0.3} \left(\frac{P_1}{P_2}\right)^{0.4}$$

The volume is thus

$$\text{Vol}_{\text{clr}} = A_{\text{clr}} \left( \frac{\Delta P}{P} \right)_{\text{clr}}^{-.41}$$

d. Heater. The heater is assumed to be a shell and tube heat exchanger with the working gas in the tubes and combustion gas out.

The following are defined:

$\left( \frac{D_h}{D} \right)_{\text{htr}}$  - diameter ratio for heater

$\Delta h_{\text{htr}}$  - enthalpy difference across the interior stream of heater

Values of  $\left( \frac{\Delta P}{P} \right)_{\text{htr}_1}$ ,  $\left( \frac{\Delta P}{P} \right)_{\text{htr}_2}$ , and  $\left( \frac{D_h}{D} \right)_{\text{htr}}$  are

estimated from the following relations:

$$\left( \frac{\Delta P}{P} \right)_{\text{htr}_2} = .0108 \pi_c^{-.01} \quad \left[ \left( \frac{\Delta P}{P} \right)_{\text{htr}_1} = .17 \right]$$

$$\left( \frac{\Delta P}{P} \right)_{\text{htr}_1} = \left( \frac{\Delta P}{P} \right)_{\text{htr}_2} \beta^{-1} \left( \frac{D_h}{D} \right)_{\text{htr}}^3$$

where

$$\beta = \left( \frac{\dot{m}_1}{\dot{m}_2} \right)^{-1.75} \left( \frac{\mu_1}{\mu_2} \right)^{-.25} \left( \frac{\rho_1}{\rho_2} \right) \left( \frac{P_1}{P_2} \right)$$

$$\left( \frac{D_h}{D} \right)_{\text{htr}} = .048 \pi_c + .214$$

Subscripts 1 and 2 refer to quantities inside and outside

the tubes respectively. Compute  $A_{htr}$  as follows:

$$A_{htr} = \left( \frac{T_2}{T_1} \right)^{\frac{\gamma}{\gamma-1}} \gamma_0 m_0 \Delta C_{p, htr}^{1.41} \left[ 1 + \left( \frac{2h}{D} \right)_{htr} \right] \left[ 1 - \alpha_0 \frac{2h}{D} \right]_{htr}^{-1} \left( \frac{2h}{D} \right)_{htr}^{-2.5}$$

where  $\tau$ ,  $\gamma$ ,  $\alpha$  are as previously defined.

Then compute  $Vol_{htr}$

$$V_{htr} = A_{htr} \left( \frac{\Delta P}{P} \right)_{htr_2}^{-1.41}$$

e. Waste Heat Boiler. The boiler is assumed to be a once through cross-counterflow type, as shown in Figure 6. High pressure is inside the tubes thus saturation pressure must be greater than the working pressure of the closed Brayton cycle.

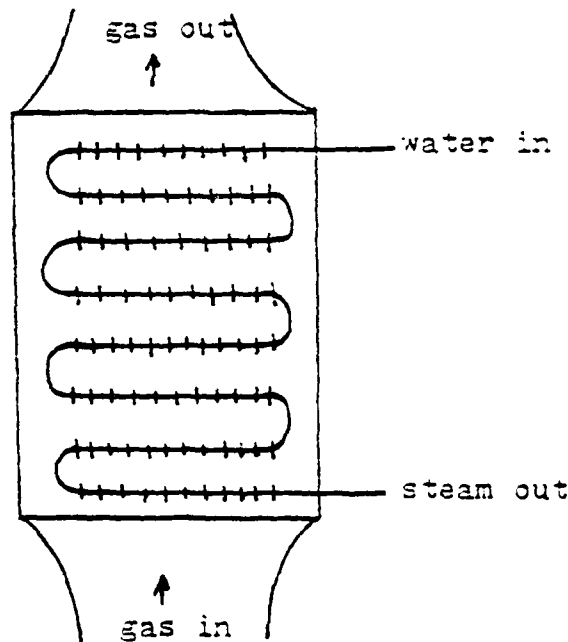


Figure 6.

Boiler volume is estimated using heat transfer relations and volumes from similar U.S. Navy COGAS (Combined Gas Turbine and Steam) designs (ref. 11).

The following are defined:

- $C_{ps}$  - ave. specific heat on steam side
- $C_p$  - ave. specific heat on air side
- NTU - Number Transfer Units
- $n_p$  - number of passes
- $A_{HT}$  - Heat transfer area
- $U$  - overall heat transfer coefficient
- $V_T$  - total volume

From a DTNSRDC (David Taylor Naval Ship Research and Development Center) study (ref.11) the following relations are obtained:

$$CR = \frac{C_{MIN}}{C_{MAX}} = \frac{\dot{m}_s C_{ps}}{\dot{m}_a C_p} \quad \text{or} \quad \frac{\dot{m}_a C_p}{\dot{m}_s C_{ps}}$$

$$ER = \frac{(P_{HTS} CR - 1)}{(P_{HTS} - 1)}$$

$$NTU = (-n_p) \ln \left\{ 1 + \frac{1}{CR} \ln \left[ \frac{1 - CR(1 - ER^{1/n_p})}{(CR - ER^{1/n_p})} \right] \right\}$$

$$A_{HT} = \frac{NTU \cdot C_{MIN}}{U}$$

For similar designs assume  $A_{HT} \propto V_T$

$$U_I \propto U_{II}$$

thus 
$$\frac{V_I}{V_{II}} \propto \frac{C_{MIN_I}}{C_{MIN_{II}}} \times \frac{NTU_I}{NTU_{II}}$$

$$V_I \propto \left( \frac{V_{II}}{C_{MIN_{II}} NTU_{II}} \right) C_{MIN_I} NTU_I$$

The term  $\left( \frac{V_{II}}{C_{MIN_{II}} NTU_{II}} \right)$  can be evaluated from known data

on previous designs to give

$$V_{WHB} = 11.53 * C_{MIN} * NTU$$

But it should be noted that the above equation assumes constant  $\left( \frac{\Delta P}{P} \right)_{WHB}$  and boiler power. If as before  $Vol \propto A_{HT}$  then from heat transfer

$$A_{HT} \propto \dot{m}_s \Delta h_s$$

thus

$$V \propto \dot{m}_s \Delta h_s$$

Correcting the above equation for power gives

$$V_{WHB} = .0017 C_{MIN} * NTU * \dot{m}_s * \Delta h_s$$

As stated previously  $Vol \propto \left( \frac{\Delta P}{P} \right)^{-.4}$

Correcting again for pressure drop yields

$$V_{NRHB} = \frac{.00045 \text{ CMIN} * \text{NTU} * \dot{m}_s * \Delta h_s \left(\frac{\Delta P}{P}\right)^{-.4}}{(ft^3)}$$

CMIN in BTU/s - °R

$\dot{m}_s$  in lbm/s

$\Delta h_s$  in BTU/lbm

2. Condenser. The condenser is assumed to be a shell and tube crossflow heat exchanger with salt water inside the tubes and steam outside.

The following are defined.

- D - inside tube diameter
- N - number of tubes
- L - length of tubes
- g - Gravitational acceleration constant
- $\Delta P_s$  - pressure drop on the salt water side
- f - friction factor
- $\rho_c$  - density of cooling water
- $V_c$  - velocity of cooling water
- $A_c$  - cross sect. free flow area on water side

- $w_c$  - flow rate of cooling water
- $q$  - heat flow in condenser
- $C_c$  -  $w_c(x)$  specific heat of cooling water ( $C_p$ )
- $\Delta T_c$  - temp. difference across the cooling water side
- $x$  - steam quality entering condenser
- $h_{fg}$  - enthalpy difference between sat. liquid and sat. steam
- $\dot{m}_s$  - mass flow of steam entering condenser

From basic heat transfer relationships

$$A_{HT} = \pi DNL$$

where

$$N = \frac{4 A_c}{\pi D^2}$$

$$L = \frac{g \Delta P_c D}{2 f \rho_c V_c^2}$$

therefore,

$$A_{HT} = \frac{2 A_c g \Delta P_c}{f \rho_c V_c^2}$$

where

$$A_c = \frac{w_c}{\rho_c V_c}$$

$$w_c = q / (C_c \Delta T_c)$$

$$q = \dot{m}_s \lambda h_{fg}$$

thus

$$A_{cond} = \frac{\Delta p \Delta P_c h_{fg} m_s X}{\rho^2 V_c^3 C_0 \Delta T_c}$$

For similar designs assume  $V_c \propto A_{cond}$

thus

$$\frac{V_c}{V_c} = \frac{\left( \frac{\Delta p \Delta P_c h_{fg} m_s X}{\rho^2 V_c^3 C_0 \Delta T_c} \right)}{\left( \frac{\Delta p \Delta P_c h_{fg} m_s X}{\rho^2 V_c^3 C_0 \Delta T_c} \right)} \left( \frac{m_s X}{m_s X} \right)$$

$\approx 1$  for similar designs assuming same  $\Delta P_c$

therefore

$$V_c = \left[ \frac{V_c}{(m_s X)} \right] (m_s X)$$

The quantity in brackets can be evaluated from known data on previous designs (ref. 11) to give

$$V_{cond} = 27.3 \dot{m}_s X \quad \text{ft}^3$$

$\dot{m}_s$  in lbm/s

#### IV. DESIGN OF A 25,000 HP PLANT

A proposed design of a 25,000 HP coal-fired combined cycle was completed. Coal combustion is accomplished using a pressurized fluidized bed (PFB). Design parameters were eventually chosen after investigating the effect of changing pressure ratios, varying  $\left(\frac{P_2}{P_1}\right)$  in the Brayton cycle, varying  $E_R$  (regenerator effectiveness), different compressor inlet temp. ( $T_1$ ) and steam condensing temp. ( $T_{13}$ ), and variations in Brayton working pressure ( $WP$ ) and saturation pressure ( $P_{min.}$ ).

a. The Fluidized Bed. The pressurized fluidized bed operates at a pressure of 3 to 10 atmospheres. Pressure is maintained by an exhaust driven compressor. For proper combustion incoming air must be preheated by the recuperator to at least 700°F. The bed material is primarily limestone which serves to capture sulfur in the coal and thus minimize  $SO_2$  emissions. A bed temperature of 1700°F is generally used to keep  $NO_x$  emissions at an acceptable level.

The fluid bed itself is about 4 ft. deep. Preheated combustion air enters the bed via a perforated bed plate underneath the bed. Pressure drop across the bed is assumed to be 10%.

The PFB is used to heat the working fluid in the closed Brayton cycle. The working fluid leaves the regenerator and

enters the tubes in the PFB. The working fluid is first heated by convection from the gas leaving the bed and is then ducted to tubes submerged in the fluid bed for final heating to the turbine inlet temp ( $T_4$ ). (Figure 7)

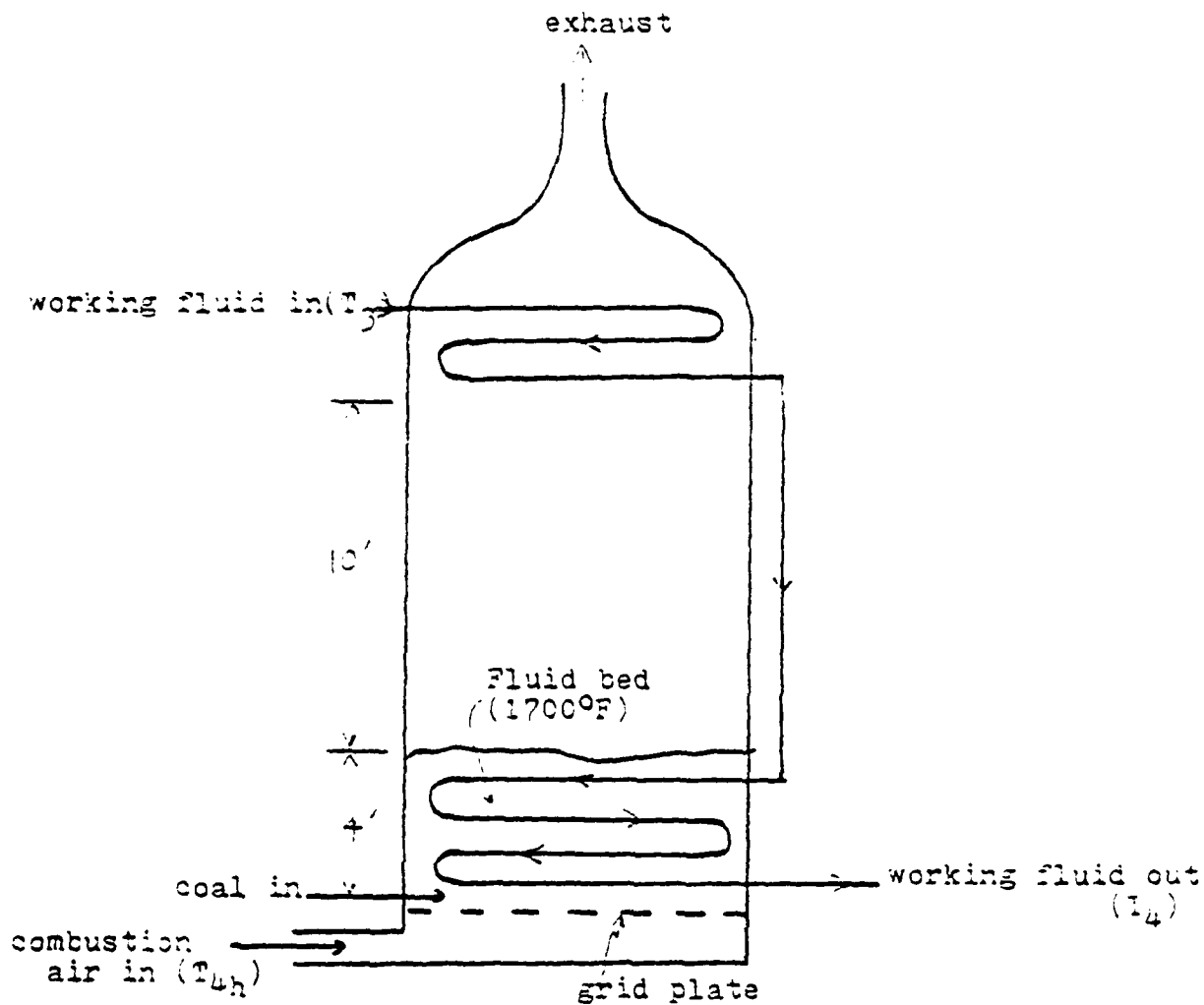


Figure 7.

b. Assumptions. The computer program was run with the following input values:

$\eta_c(P)$	=	.88
$\eta_r(P)$	=	.91
$E_R$	=	.88
$\eta_p(S)$	=	.80
$\eta_r(S)$	=	.88
$\left(\frac{\Delta P}{P}\right)_-$	=	.10
$\eta_{ARB}$	=	.94
$T_1$	=	540.0 °R
$T_2$	=	2060.0 °R
$T_{1B}$	=	540.0 °R
$\Delta T$	=	+35.0 °R
$NP$	=	135.0 psi
$P_{SAT}$	=	200.0 psi (want at least 50 psi greater than NP)
Power	=	25000 HP
$T_{1h}$	=	535.0 °R
$T_{7h}$	=	760 °R (limited by acid corrosion in the turbine)
$\eta_c(P)_h$	=	.85
$\eta_r(P)_h$	=	.89
$\phi$	=	.90 (11% excess air)

In addition it was assumed that scoop injection could be used for both the cooler and condenser at speeds greater than 10 knots, therefore power requirements for salt water circulating

pumps were excluded in the calculations.

c. Results. The computer output is provided in Appendix B. Note that the saturation pressure for pressure ratios of 2 and 3 were below the 200 psia specification. This is due to the fact that the low pressure stream leaving the regenerator is at a temperature below the saturation temp. at 200psia. A plot of  $\eta_-$  vs.  $\pi_c$  and  $Vol_{total}$  vs.  $\pi_c$  is shown in Figure 8.

Note that the volume increases sharply above  $\pi_c = 4$  due largely to the rapid growth in the waste heat boiler. Maximum  $\eta_-$  occurs at around  $\pi_c = 6$ . To investigate the effect of  $\left(\frac{\Delta P}{P}\right)_m$  on  $\eta_-$  and  $Vol_+$ , the program was run for  $\left(\frac{\Delta P}{P}\right)_m = .04, .06, .08, .10, \text{ and } .12$  between  $\pi_c$  of 4 and 9.

The results plotted on Figure 9 show that significant gains in  $\eta_-$  can be realized with very little increase in  $V_m$  for the range of 4-6 pressure ratio. The effect of changing  $E_R$  (regenerator effectiveness) in this range with a  $\left(\frac{\Delta P}{P}\right)_m = .05$  was further investigated.

The results listed in Table 1 show no increase in efficiency as  $E_R$  is reduced. Furthermore, volume increases sharply as a greater percentage of the work is being done by the Rankine cycle as  $E_R$  decreases. Thus for greatest efficiency with minimum volume, cycle operation should be at the highest  $E_R$  practicable.

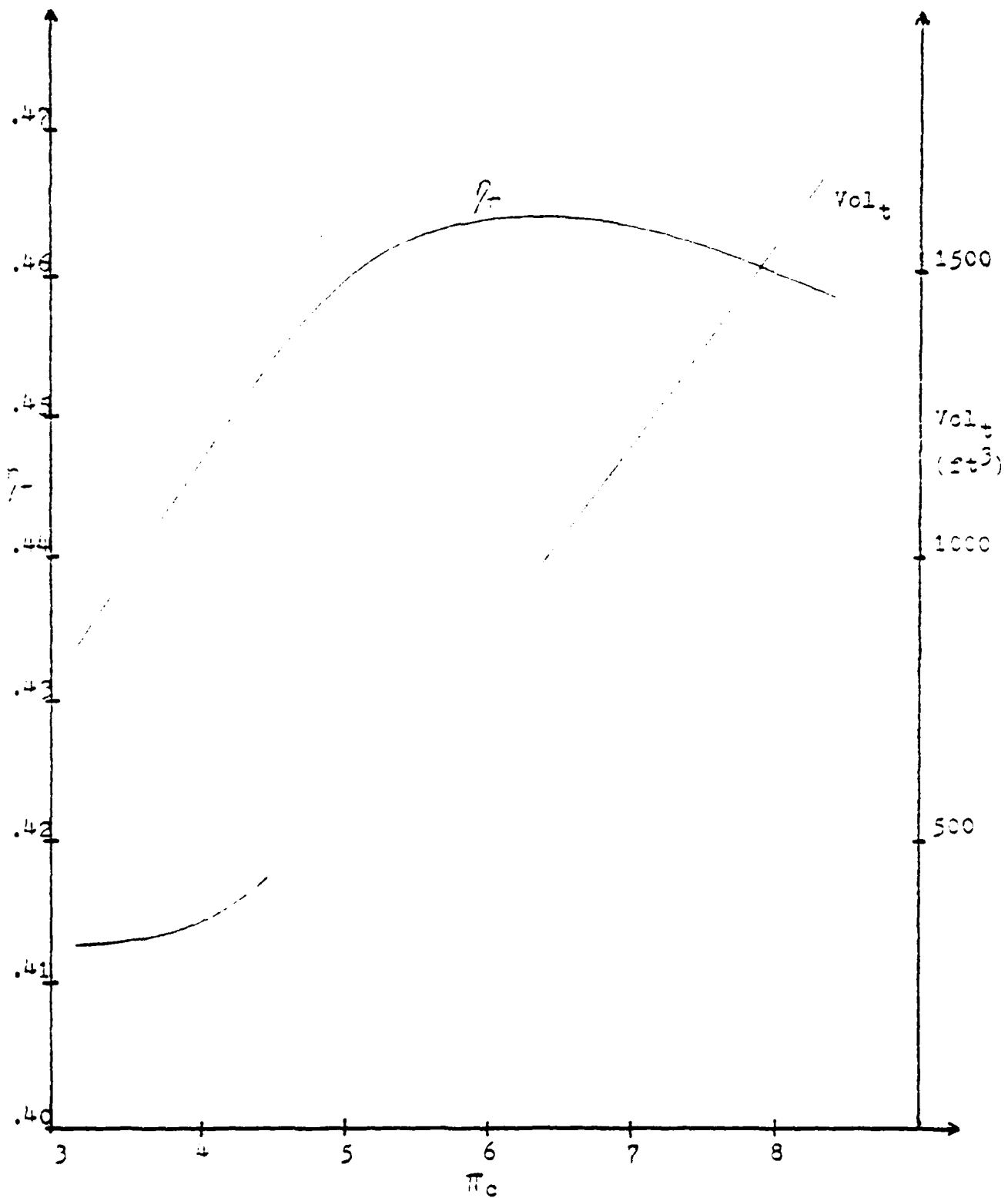


Figure 3.

Figure 9.

$$\left(\frac{\Delta p}{p}\right)_T = .04$$

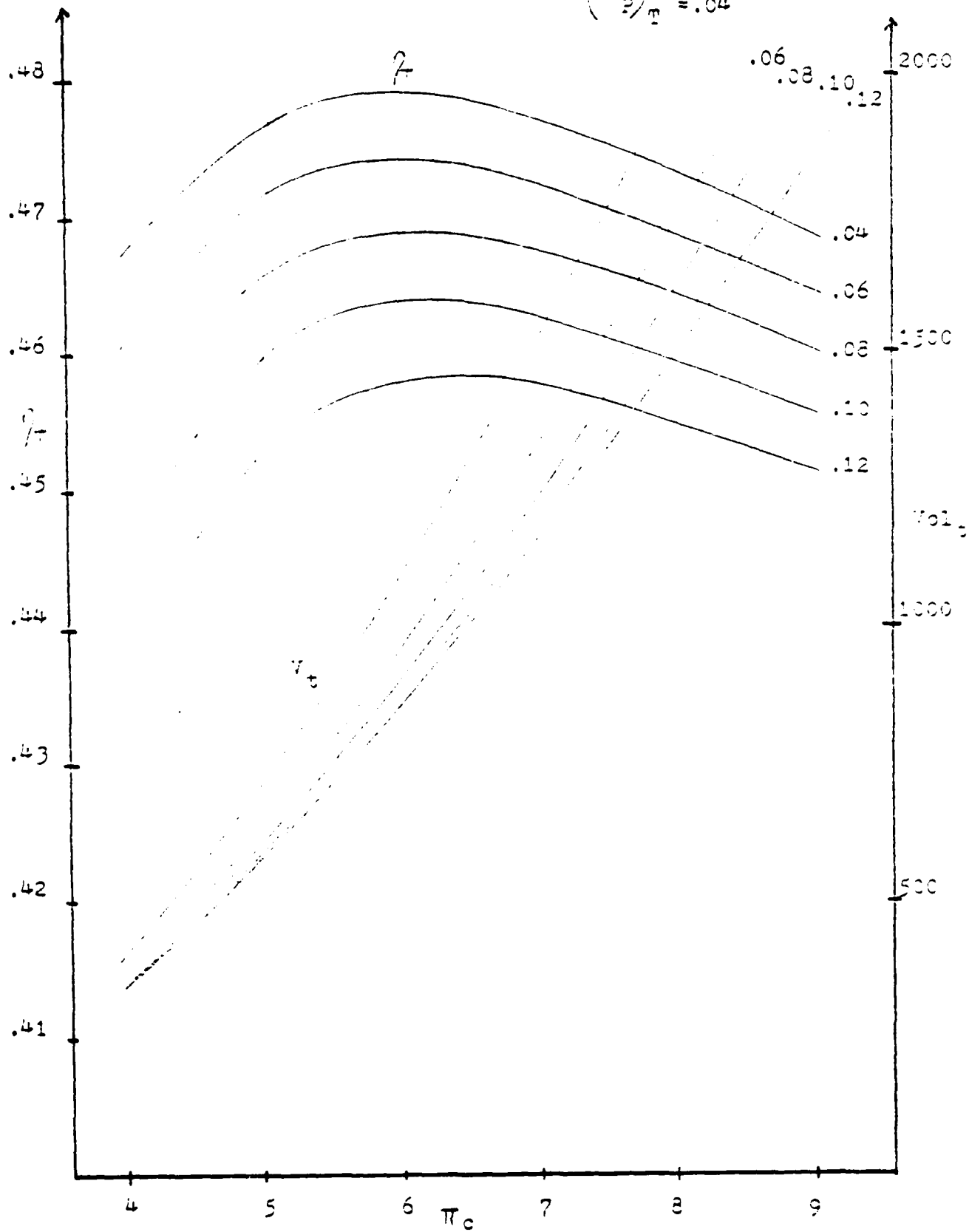


Table 1

<u>c</u>	<u>E<sub>R</sub></u>	<u>t</u>	<u>Vol<sub>t</sub> (ft<sup>3</sup>)</u>
3	.88	.452	335
	.80	.423	646
	.50	.402	7038
4	.88	.464	408
	.80	.454	811
	.50	.432	4350
5	.88	.474	724
	.80	.464	1083
	.50	.447	3741
6	.88	.475	1050
	.80	.471	1396
	.50	.456	3508
7	.88	.473	1450
	.80	.471	1750
	.50	.460	3435

To investigate the effect of changes in  $T_1$  (compressor inlet temp.) runs were made on 4 different temperatures and the results shown in Figure 10. As expected efficiency decreased with increasing  $T_1$  with very little change in the range of interest 4-4.5  $\pi_c$ . Volume on the other hand decreased slightly for  $\pi_c$  less than 3.5 but increased significantly above that. Thus for best efficiency and least volume  $T_1$  should be kept as close to cooling water temperature as possible.

Finally, changes in working pressure of the Brayton cycle were investigated. Decreases in working pressure may require additional volume of Brayton cycle components yet at the same time allow a decrease in Rankine cycle steam pressure (recall 50°R pressure differential between boiler streams). This will in turn increase cycle efficiency yet further increase volume. These results are born out in Figure 11.

d. System Selection. In accordance with the design criteria the highest thermal efficiency considered is 0.487 (Figure 11). Thus it is desired to select the plant with minimum volume at  $\eta_t = .482$ .

Figure 11 shows that only those alternatives with Brayton cycle working pressures of 70psi and 100psi meet the efficiency requirement. Of these two the 100psi case has minimum volume at desired efficiency.

However, the problem does not end here. If one looks at

Figure 10.

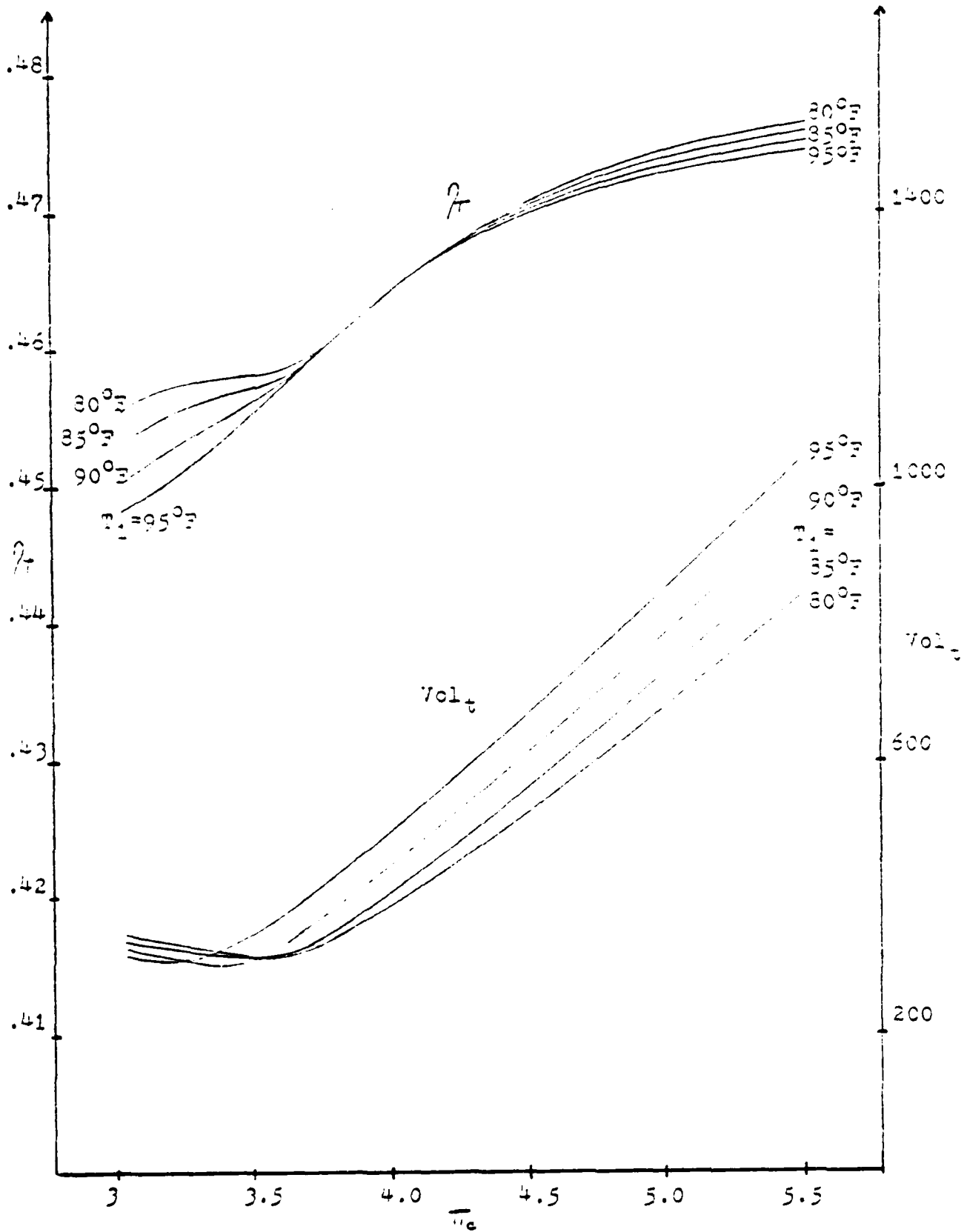
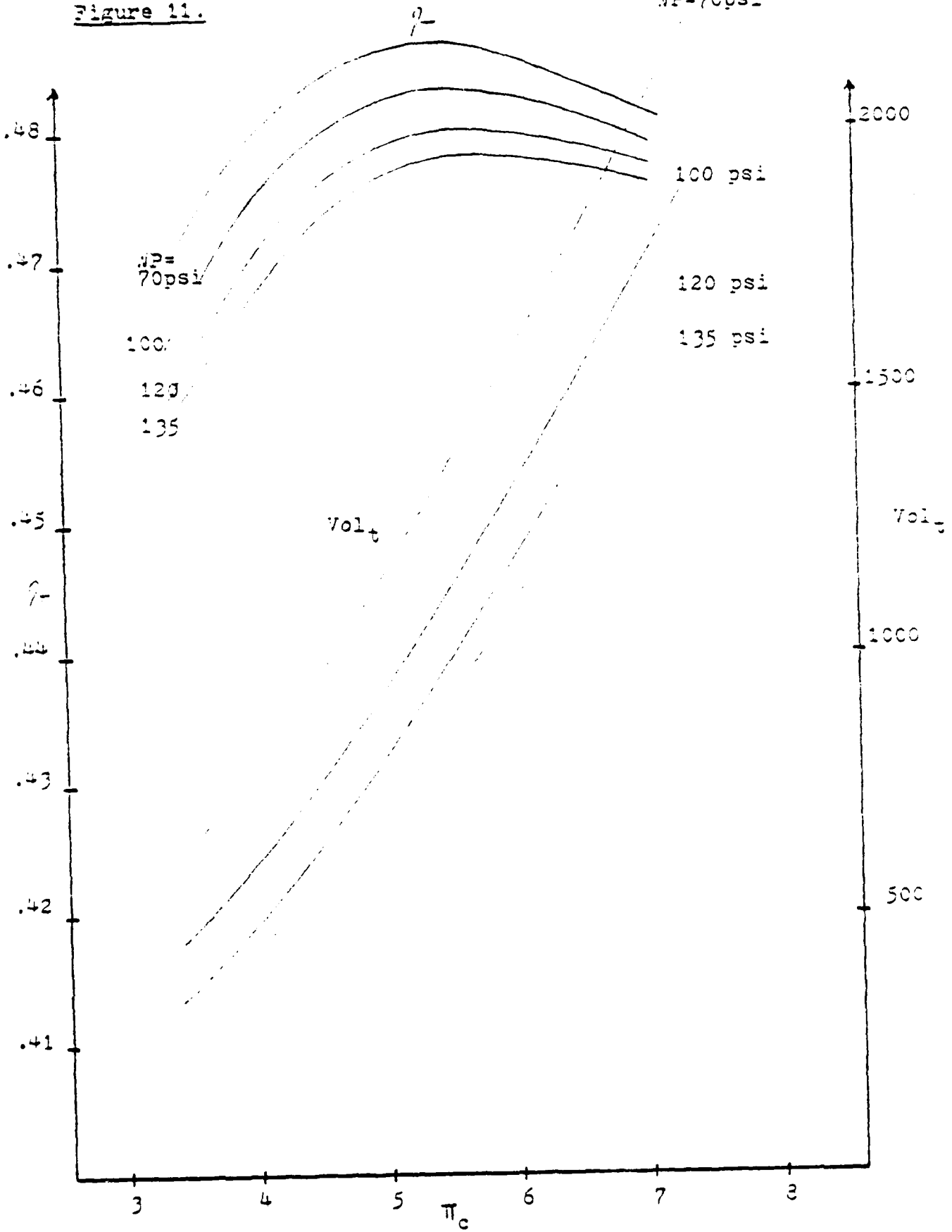


Figure 11.

NP=70psi



the steam quality leaving the turbine at the  $\pi_c = 5$ , WP = 100 psi point it is of the order of 0.34. This is a little lower than normally desired for design. In fact, the steam quality of all alternatives thus far considered within the range of interest is low. If a steam quality of order .37 is desired the current design pt. can change in one of 3 ways as follows:

- 1) Raise steam condensing temp ( $T_{1S}$ )
- 2) Lower minimum saturation pressure ( $P_{min}$ )
- 3) or a combination of the above two

Through trial and error it was found that case 1 gave the greatest benefit with the least penalty. Computer runs were made in the 4-5  $\pi_c$  range with the steam condensing temp raised to 560°R for both the 70 and 100psi alternatives. The results show a substantial increase in quality, slight decrease in efficiency and very little change in total volume (Table 2).

(psi) Working Pressure	$\pi_c$	$\eta_t$	x	Vol <sub>t</sub> (ft <sup>3</sup> )
70	4.5	.480	.864	948.3
70	5.0	.482	.871	1140.6
100	5.0	.479	.862	956.5

Table 2.

The 70 psi designs have better steam quality and  $\eta_t$  than the best 100 psi case. In addition, at 4.5  $\pi_c$  the volume is lower. Between the two 70 psi cases above a trade-off exists between  $\eta_t$  and Vol<sub>t</sub>. Assume that volume comparable to the case

of  $\bar{\pi}_c = 5$ ,  $WP = 100$  psi,  $T_{1S} = 540^\circ R$  discussed above (Figure 11) is desired. If this is the case then the new design point is at a Brayton cycle working pressure of 70 psi,  $\bar{\pi}_c = 4.5$ ,  $T_{1S} = 560^\circ R$ . The results of this design are summarized in the following computer printout:

BRAYTON CYCLE: PRESSURE RATIO = 4.50  
 WORKING PRESSURE = 70.0  
 TOTAL PRESSURE DROP = .05  
 MASS FLOW (LBM/S) = 206.93

STATE	TEMP (DEG R)	DPP	DHD	VOL (CU FT)
1	540.0			
2	376.0			
3	1403.9			
4	2060.0			
5	1475.9			
6	948.0			
7	809.2			
COMPONENT	DPP	DHD	VOL (CU FT)	
REGEN	.010	.950	26.5	EFF = 0.88
TURBINE			5.5	EFF (P) = 0.91
COOLER	.009	.490	193.1	
COMPRESSOR			29.7	EFF (P) = 0.88
HEATER	.0006			
BOILER	.030			EFF = 0.94

SUMMARY: THERMAL EFF = 0.280  
 HEATER EFF = 0.933 (PHI) = 0.901  
 SFC (LBM/HP-HR) = 0.140  
 VOL TOTAL (CU FT) = 948.3  
 POWER (HP) = 25000.0  
 WORK FRAC BY STEAM CYCLE = 0.101

HEATER CYCLE: PRESSURE RATIO = 4.79  
 TOTAL PRESSURE DROP = .43  
 AIR FLOW (LBM/S) = 36.85  
 FUEL FLOW (LBM/S) = 3.06

STATE	TEMP (DEG R)	DPP	DHD	VOL (CU FT)
1H	535.0			
2H	335.2			
3H	1440.5			
4H	4809.8			
5H	1503.9			
6H	945.0			
7H	760.0			
COMPONENT	DPP	DHD	VOL (CU FT)	
RECUP	.313	.650	1.9	EFF = 0.91
TURBINE			0.7	EFF (P) = 0.89
HEATER	.019	.430	31.4	
COMPRESSOR			10.8	EFF (P) = 0.85

RANKINE CYCLE: SATURATION PRESSURE = 120.0  
 STEAM FLOW (LBM/S) = 5.69  
 FLOW RATIO = 0.0275

STATE	TEMP (DEG R)	PRESSURE (PSI)
1S	560.0	0.9
2S	575.0	120.0
SF	801.2	120.0
3S	913.0	120.0
4S	560.0	0.9
QUAL		0.864
COMPONENT	VOL (CU FT)	
BOILER	507.9	
TURBINE	6.5	EFF (IS) = 0.88
CONDENSER	134.2	

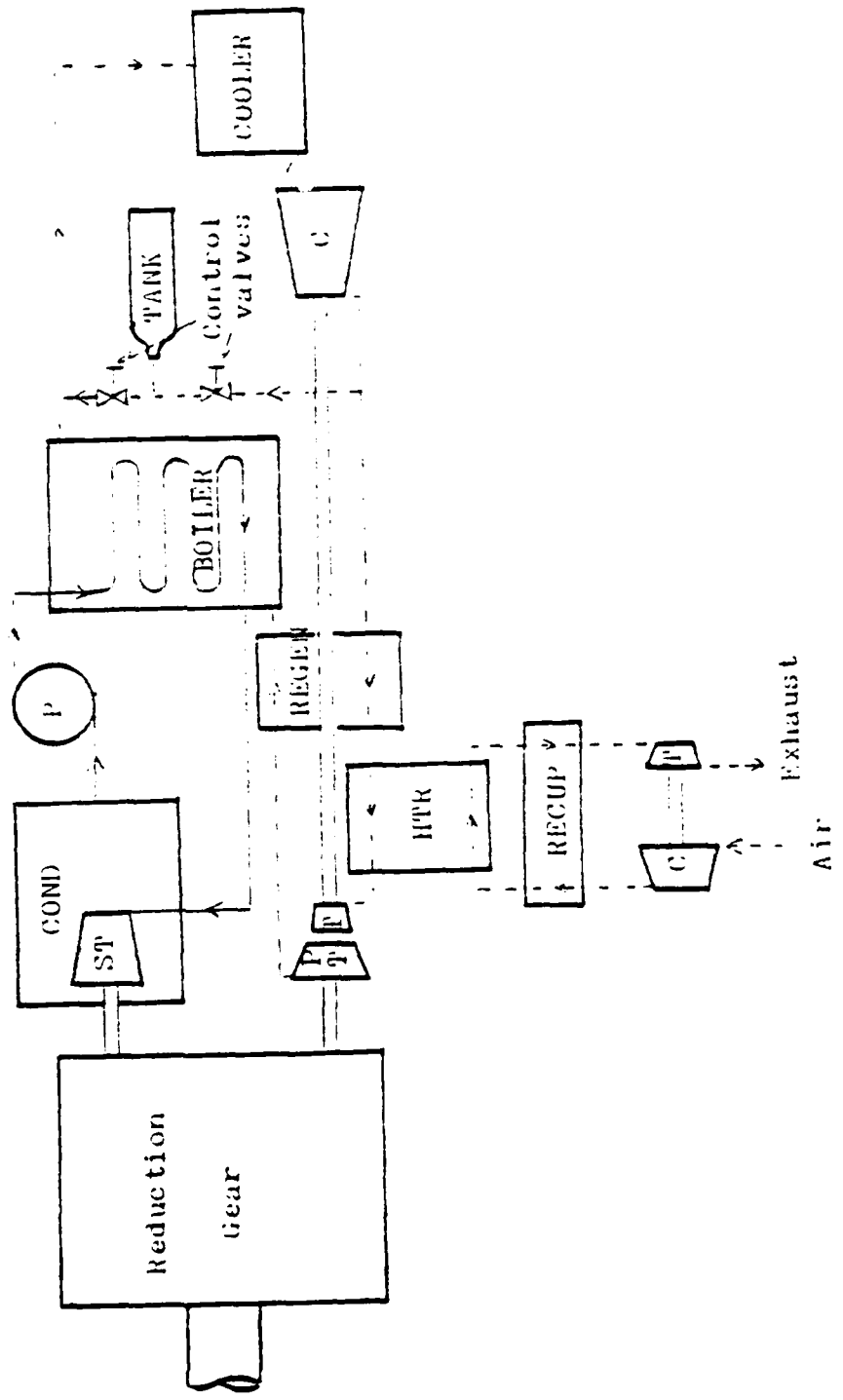
## 7. APPLICATION

The application of this system to Navy ships has many implications. One of which is the fact that neither Closed Brayton nor combined cycles have been previously used. However, there is a considerable effort at this time to get COGAS (Combined Gas Turbine and Steam) systems on board Navy ships. These systems are all limited to burning oil fuels. The Closed Brayton combined cycle when equipped with a multi-fuels heater offers the additional flexibility of burning the cheapest or most readily available fuel.

Advantages of the Closed Brayton combined cycle are:

- 1) The Brayton cycle operates at temperatures substantially below the material limit than in the open cycle gas turbines resulting in cheaper, more reliable, and longer life components.
- 2) Low pressure steam systems are well proven, and have significantly less water chemistry problems than higher pressure ones.
- 3) As load decreases and fuel flow is cut back, the control valves (Figure 12) between the compressor outlet and cooler inlet can be opened as necessary (keeping max. temp and speed constant) so as to ensure that the vector diagrams of all sections of the turbomachinery blading remain unchanged. Turbine and compressor efficiencies will remain essentially the same producing high  $\eta_t$  at part load. This requires use of a CRP

Functional Component Arrangement



(controllable reversible pitch) propeller to maintain constant shaft speed at part loads.

Disadvantages of the Closed Brayton combined cycle are:

1) Higher overall system weight and volume due to the additional heat exchangers and piping required for the Closed Brayton cycle.

2) A complex, integrated control system is required to coordinate control of the combined cycle, fuel flow, and CRP at part loads.

3) Fluidized bed combustion is not a fully developed engineering concept. Land based prototypes have been built and operated with limited but increasing levels of success. A shipboard prototype is perhaps 5 years in the future with production of a marinized version at least 10 years away.

4) If coal is to be used as the primary fuel, it should be noted that it has a lower heating value per ton than oil. The result is a larger potentially more expensive (greater acquisition cost) ship for the same military mission.

5) Reaction time with coal fired fluidized bed combustors to load changes are generally slower than that for oil heaters necessitating in a separate fuel oil system for rapid increases in load.

## VI. CONCLUSIONS AND RECOMMENDATIONS

The Closed Brayton combined cycle offers an attractive alternative system for many shipboard applications. As with the first Arab oil embargo, subsequent cut-offs of Arab oil could result in decreased steaming days and a lower overall readiness of the U.S. Navy's defense posture.

If our ships could have the option of burning the most readily available fuel, this reduction in readiness can be avoided by switching to coal, a fuel source in great abundance in the U.S.

Paramount in the engineering of a successful multi-fuels propulsion plant is the development of a marinized fluid bed combustor. The design of heat exchangers and other turbo-machinery used in the combined cycle are well within the state of the art of present technology.

It is thus that the author concludes the following:

1) The design of a modern coal burning combined cycle is within the reach of present technology.

2) This combined cycle would offer high efficiency at both rated load and part load due to the unique controlling aspect of the Closed Brayton cycle.

3) Weight and volume of a Closed Brayton combined cycle would be greater than that of an equivalently rated CCGAS type system.

4) Coal offers the benefit of a readily available,

relatively cheap fuel at the expense of increased ship size and acquisition cost due to lower BTU heat value per ton when compared to oil.

The author makes the following recommendations:

1) Development of a land based test site of a Closed Brayton combined cycle equipped with a fluid bed heater should be considered.

2) A pressurized fluidized bed combustor suitable to marine applications should be developed.

3) A shipboard prototype system should be integrated on a U.S. Navy ship to attempt to quantitatively define the shipboard impact of the system.

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## APPENDIX A

The computer program performs a thermodynamic analysis and component volume computation for various specified Brayton cycle compressor pressure ratios.

The program accepts as input the following quantities:

- $\eta_c(P)$  - polytropic compressor efficiency (Brayton cycle)
- $\eta_t(P)$  - polytropic turbine efficiency (Brayton cycle)
- $E_R$  - regenerator effectiveness
- $\eta_{p(is)}$  - isentropic pump efficiency (Rankine cycle)
- $\left(\frac{\Delta P}{P}\right)_T$  - total pressure drop around Brayton cycle loop
- $\eta_{WHB}$  - efficiency of the waste heat boiler
- $T_1$  - compressor inlet temp. (Brayton cycle)
- $T_4$  - turbine inlet temp (Brayton cycle)
- $T_{1S}$  - steam condensing temp.
- $\Delta T$  - min. temp diff. between streams in WHB (at PP and  $T_6$ )
- $P_{SAT}$  - min. saturation pressure in the Rankine cycle
- Power - net power out of the combined cycle
- $T_{1h}$  - compressor inlet temp. (heater cycle)
- $T_{7h}$  - turbine exit temp. (heater cycle)
- $\eta_c(P)_h$  - polytropic compressor efficiency (heater cycle)
- $\eta_t(is)$  - isentropic turbine efficiency (Rankine cycle)

- $\eta_{t,p}$  - polytropic turbine efficiency (heater cycle)
- $\phi$  - equivalence ratio
- WP - working pressure in the Brayton cycle.

Output is as shown in Appendix B.

The main program performs the thermodynamic analysis of the closed Brayton cycle and the Rankine cycle. Functions performed by the various subfunctions are as follows:

- 1) Subroutine HEATER performs a thermodynamic analysis of the heater cycle.
- 2) Subroutine DHD computes  $\frac{D_h}{S}$  for the regenerator, recuperator, cooler and heater.
- 3) Subroutine DPP calculates  $\frac{\Delta P}{P}$  for the regenerator, recuperator, cooler, heater and boiler.
- 4) Subroutine TURVOL finds turbine volumes.
- 5) Subroutine COMPVOL finds compressor volumes.
- 6) Subroutine REGEN computes the regenerator volume.
- 7) Subroutine RECUP computes the recuperator volume.
- 8) Subroutine COOLER computes the cooler volume.
- 9) Subroutine COMBUSTOR computes the heater volume.
- 10) Subroutine WHEVOL computes the waste heat boiler volume.
- 11) Subroutine CONDVOL computes the condenser volume.
- 12) Subroutine STMTAB is a computerized version of the steam tables. Reproduced from ref. 15.

```

DIMENSION CR(30),SATLIQ(3),STEAM(3),TPP(12),WR(11)
REAL NCP,NTP,NPIS,NTIS,NWHB,NT,L1,L2,KO
REAL NCPH,NTPH,MB,MS,MA,MF,NH,N,IT,KI1,NPP
REAL LHV,M,M1,M2,NTU
COMMON /STM/PRESS,TEMP,QUAL,SATLIQ,STEAM
COMMON /HTR/NH,PRH,DPPH,T2H,T3H,T4H,T5H,T6H,MA,MF
COMMON /DIA/DHDREG,DHDCLR,DHDHTR,DHDREC
COMMON /PRES/DPPWHB,DPPREG,DPPCLR,DPPREC,DPH1,DPH2,DHDHT
COMMON /COMB/DPPRG,DPPRC,DPPHE,DHDHR,DPHE2
10 READ(5,10) NCP,NTP,ER,NPIS,NTIS,DP,NWHB,T1,T4,TIS,DT,PMIN,K
   FORMAT (7F4.3,5F7.1,I2)
15 READ(5,15) PWR,T1H,T7H,NCPH,NTPH,PHI,WP
   FORMAT (F8.1,2F6.1,3F5.3,F6.1)
20 READ(5,20) (CR(I),I=1,K)
   FORMAT (<K>F5.2)
   R=.068544
   DO 200 I=1,K
     PR=CR(I)
     Z=CP1(T1)+(R/NCP)*LOG(PR)
     T2=EXP(Z/.2475)
     CALL ITER (T2,Z)
     TR=1/(1-DP)/PR
     Z=CP1(T4)+R*NTP*LOG(TR)
     T5=EXP(Z/.2475)
     CALL ITER (T5,Z)
     IF(T2 .GT. T5) GO TO 30
     T6=T5-ER*(T5-T2)
     T3=T2+ER*(T5-T2)
     GO TO 40
30   T6=T5
     T3=T2
40   L1=T1
     L2=1122.0
     IF(L2 .GT. T6) GO TO 50
     GO TO 60
50   L2=T6-(T6-T1)/10.
60   TPP(1)=L2
     WR1=0.
     C=(L2-L1)/10.
     DO 70 J=1,11
       TSF=TPP(J)-DT
       T3S=T6-DT
       T=TSF-460
       CALL STMTAB (2,T,0.)
       PSF=PRESS
       HSF=SATLIQ(2)
       T=T3S-460
       CALL STMTAB (7,PSF,T)
       H3S=STEAM(2)
       S3S=STEAM(3)
       T=T1S-460

```

```

CALL STMTAB (2,T,O.)
P4S=PRESS
V1S=SATLIQ(1)
H1S=SATLIQ(2)
S1S=SATLIQ(3)
CALL STMTAB (9,P4S,S3S)
H4SIS=STEAM(2)
H4S=H3S-NTIS*(H3S-H4SIS)
CALL STMTAB (8,P4S,H4S)
X=QUAL
V4S=STEAM(1)
H2SIS=H1S+V1S*(PSF-P4S)
H2S=H1S+(H2SIS-H1S)/NPIS
T2S=T1S+15.
B=NWHB*(CP2(T6)-CP2(TPP(J)))/(H3S-HSF)
Z=ACP(TPP(J))*TPP(J)-B*(HSF-H2S)/NWHB
T7=TPP(J)
CALL ITER2 (T7,Z)
WR(J)=B*(H3S+H1S-H4S-H2S)
IF(J .EQ. 1) GO TO 68
IF(T7 .LT. T1) GO TO 75
IF(PSF .LT. PMIN) GO TO 75
IF(WR(J) .GT. WR1) GO TO 68
IF(X .GT. .37) GO TO 75
58 WR1=WR(J)
TPP(J+1)=TPP(J)-C
70 CONTINUE
GO TO 76
75 IF(ABS(TPP(J)-TPP(J-1)) .LT. .1) GO TO 76
L1=TPP(J)
L2=TPP(J-1)
GO TO 60
76 WB=CP2(T4)+CP2(T1)-CP2(T5)-CP2(T2)
QIN=CP2(T4)-CP2(T3)
NT=(WB+WR(J))/QIN
MB=.707*PWR/(WB+WR(J))
MS=B*MB
QB=MB*QIN
CALL HEATER (QB,T1H,T7H,NCPH,NTPH,PHI,T3,T4)
CALL DHD(PR)
DHOHT=DHDHTR
K=1
77 * CALL DPP(T6,T7,PR,DP,ER,T2,T3,DPPH,T4H,T5H,T4,PRH,WP,MB,MA
, MF,K)
G=1.33
N=G/(G-(G-1.)*NTP)
P=WP*(PR-DPPREG)
V=1./ARHO(T4,P)
VMNTURB=0.0
CALL TURBVOL (N,MB,V,TR,T4,VMNTURB)
G=1.39

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N=G/(G-(G-1.)*NTPH)
P=14.7*(PRH-DPPREC)
V=1./ARHO(T6H,P)
M=MA+MF
VHTRTURB=0.0
TRH=1./(1.-DPPH)/PRH
CALL TURBVOL (N,M,V,TRH,T6H,VHTRTURB)
T=T1S/T3S
P=P4S/PSF
N=1./(1.-LOG(T)/LOG(P))
VSTMTURB=0.0
CALL TURBVOL (N,MS,V4S,P,T3S,VSTMTURB)
G=1.4
N=G/(G-(G-1.)/NCP)
V=1./ARHO(T1,WP)
VMNCOMP=0.0
CALL COMPVOL (N,MB,V,PR,VMNCOMP)
V=1./ARHO(535.,14.7)
VHTRCOMP=0.0
CALL COMPVOL (N,MA,V,PRH,VHTRCOMP)
D=.125
VREGEN=0.0
CALL REGEN (T2,T3,T5,T6,WP,D,MB,PR,DPPREG,DHDREG,VREGEN)
VRECUP=0.0
CALL RECUP (T2H,T3H,T5H,T6H,PRH,DPPH,D,MA,MF,DPPREC,VRECUP)
D=.25
VCLR=0.0
CALL COOLER (T7,T1,WP,D,NTP,MB,DHDCLR,DPPCLR,VCLR)
DPPRG=DPPREG
DPPRC=DPPREC
DPPHE=DPPH
DHDHR=DHDHTR
DPHE2=DPH2
VHTR=0.0
CALL COMBUSTOR (T3,T4,T4H,T5H,WP,PR,D,MB,PRH,MA,MF,VHTR)
VWHB=0.0
CALL WHBVOL (MB,MS,T6,T7,NWHB,H2S,H3S,DPPWHB,VWHB)
VCOND=0.0
CALL CONDVOL (MS,X,VCOND)
VOLT=VMNTURB+VHTRTURB+VSTMTURB+VMNCOMP+VHTRCOMP+VREGEN+VRECUP
* +VCLR+VHTR+VWHB+VCOND
IF(K .EQ. 1) GO TO 78
IF(VOLT .GT. VOL1) GO TO 81
IF((DPPCLR-.002) .LT. 0.0) GO TO 81
78 K=K+1
VOL1=VOLT
V1=VCLR
V2=VWHB
GO TO 77
81 VOLT=VOL1
VCLR=V1

```

```

      YWHB=V2
      WRITE(6,82) PR,WP,DP,MB
82     FORMAT('1','BRAYTON CYCLE: PRESSURE RATIO=',F5.2/1X,'WORKING
      * PRESSURE=',F5.1/1X,'TOTAL PRESSURE DROP=',F3.2/1X,'MASS FLOW
      * (lbm/s)=',F6.2/10X,'STATE TEMP(deg R)')
      WRITE(6,83) T1
83     FORMAT(12X,'1',5X,F6.1)
      WRITE(6,84) T2
84     FORMAT(12X,'2',5X,F6.1)
      WRITE(6,85) T3
85     FORMAT(12X,'3',5X,F6.1)
      WRITE(6,86) T4
86     FORMAT(12X,'4',5X,F6.1)
      WRITE(6,87) T5
87     FORMAT(12X,'5',5X,F6.1)
      WRITE(6,88) T6
88     FORMAT(12X,'6',5X,F6.1)
      WRITE(6,89) TPP(J)
89     FORMAT(12X,'PP',5X,F6.1)
      WRITE(6,90) T7
90     FORMAT(12X,'7',5X,F6.1//5X,'COMPONENT DPP DHD VOL(cu ft)')
      WRITE(6,91) DPPREG,DHDREG,VREGEN,ER
91     FORMAT(7X,'REGEN',4X,F4.3,1X,F4.3,1X,F7.1,2X,'EFF=',F4.2)
      WRITE(6,92) VMNTURB,NTP
92     FORMAT(6X,'TURBINE',15X,F5.1,2X,'EFF(P)='F4.2)
      WRITE(6,93) DPPCLR,DHDCLR,VCLR
93     FORMAT(6X,'COOLER',4X,F4.3,1X,F4.3,3X,F5.1)
      WRITE(6,94) VMNCOMP,NCP
94     FORMAT(4X,'COMPRESSOR',14X,F5.1,2X,'EFF(P)='F4.2)
      WRITE(6,95) DP41
95     FORMAT(6X,'HEATER',4X,F5.4)
      WRITE(6,96) DPPWHB,NWHB
96     FORMAT(6X,'BOILER',4X,F4.3,15X,'EFF='F4.2/)
      WRITE(6,100) PRH,DPPH,MA,MF
100    FORMAT(1X,'HEATER CYCLE: PRESSURE RATIO=',F5.2/1X,'TOTAL
      * PRESSURE DROP=',F3.2/1X,'AIR FLOW(lbm/s)=',F6.2/1X,'FUEL
      * FLOW(lbm/s)=',F6.2/10X,'STATE TEMP(deg R)')
      WRITE(6,101) T1H
101    FORMAT(12X,'1h',5X,F6.1)
      WRITE(6,102) T2H
102    FORMAT(12X,'2h',5X,F6.1)
      WRITE(6,103) T3H
103    FORMAT(12X,'3h',5X,F6.1)
      WRITE(6,104) T4H
104    FORMAT(12X,'4h',5X,F6.1)
      WRITE(6,105) T5H
105    FORMAT(12X,'5h',5X,F6.1)
      WRITE(6,106) T6H
106    FORMAT(12X,'6h',5X,F6.1)
      WRITE(6,107) T7H
107    FORMAT(12X,'7h',5X,F6.1//5X,'COMPONENT DPP DHD VOL(cu ft)')

```

```

* )
  ERH=(T3H-T2H)/(T5H-T2H)
  WRITE(6,110) DPPREC,DHDREC,VRECUP,ERH
110  FORMAT(7X,'RECUP',4X,F4.3,1X,F4.3,1X,F7.1,2X,'EFF=',F4.2)
  WRITE(6,111) VHTRTURB,NTPH
111  FORMAT(6X,'TURBINE',15X,F5.1,2X,'EFF(P)=',F4.2)
  WRITE(6,112) DPH2,DHDHTR,VHTR
112  FORMAT(6X,'HEATER',4X,F4.3,1X,F4.3,3X,F5.1)
  WRITE(6,113) VHTRCOMP,NCPH
113  FORMAT(4X,'COMPRESSOR',14X,F5.1,2X,'EFF(P)=',F4.2/)
  WRITE(6,120) PSF,MS,B
120  FORMAT(1X,'RANKINE CYCLE: SATURATION PRESSURE=',F6.1/1X,
* 'STEAM FLOW(lbm/s)=' ,F6.2/1X,'FLOW RATIO=' ,F6.4/10X,'STATE
* TEMP(deg R)  PRESSURE(psi)')
  WRITE(6,121) T1S,P4S
121  FORMAT(12X,'1s',5X,F6.1,8X,F6.1)
  WRITE(6,122) T2S,PSF
122  FORMAT(12X,'2s',5X,F6.1,8X,F6.1)
  WRITE(6,123) T3S,PSF
123  FORMAT(12X,'3s',5X,F6.1,8X,F6.1)
  WRITE(6,124) T4S,PSF
124  FORMAT(12X,'4s',5X,F6.1,8X,F6.1)
  WRITE(6,125) T1S,P4S,X
125  FORMAT(12X,'4s',5X,F6.1,8X,F6.1,2X,'QUAL=',F5.3/)
  WRITE(6,128) VWHB
128  FORMAT(5X,'COMPONENT VOL(cu ft)'/6X,'BOILER',5X,F6.1)
  WRITE(6,129) VSTMTURB,NTIS
129  FORMAT(6X,'TURBINE',5X,F5.1,2X,'EFF(IS)=',F4.2)
  WRITE(6,130) VCOND
130  FORMAT(5X,'CONDENSER',4X,F5.1/)
  WRITE(6,135) NT
135  FORMAT('1','SUMMARY:THERMAL EFF=',F5.3)
  WRITE(6,136) NH,PHI
136  FORMAT(9X,'HEATER EFF=',F5.3,' (PHI=',F4.2,')')
  SFC=MF*3600./PWR
  WRITE(6,137) SFC,VOLT,PWR
137  FORMAT(9X,'SFC(lbm/HP-hr)=' ,F5.3/9X,'VOL TOTAL(cu ft)=' ,F6.1/
*9X,'POWER(HP)=' ,F7.1)
  RANKINE=WR(J)/WB
  WRITE(6,138) RANKINE
138  FORMAT(9X,'WORK FRAC BY STM CYCLE=' ,F5.3)
200  CONTINUE

STOP
END
FUNCTION CP1(T)
CP1=.2475*LOG(T)-(3.759E-5*T)+(2.553E-8*T**2)-(4.103E-12*T**3)
RETURN
END
FUNCTION CP2(T)
CP2=.2475*T-(1.379E-5*T**2)+(1.702E-8*T**3)-(3.078E-12*T**4)
RETURN

```

```

END
FUNCTION AMU(T)
TK=5.*T/9.
AMU=TK**1.5*1.E-6/(TK+110.4)
RETURN
END
FUNCTION ARHO(T,P)
R=53.35
ARHO=P**144./R/T
RETURN
END
FUNCTION AK(T,P)
A=.5325E-5
B=215.4
C=12.
TK=5.*T/9.
AKC=(A*TK**5)/(1.+B*10.**(-1.*C/TK)/TK)**413.6
AK=(AKC+(1.464E-5*(16.02*ARHO(T,P))**1.23))**.573/3600.
RETURN
END
FUNCTION APR(T,P)
CP=ACP(T)
XMU=AMU(T)
KK=AK(T,P)
APR=CP*XMU/KK
RETURN
END
FUNCTION ASIGMA(T,P)
ASIGMA=17.214*(6223.*AK(T,P))**(-1.41)**(1.46*AMU(T))**1.23*
*(1./APR(T,P))**.564*(1./(16.02*ARHO(T,P))**.41)
RETURN
END
FUNCTION ACP(T)
ACP=.2475-3.759E-5*T+5.106E-8*T**2-1.231E-11*T**3
RETURN
END

```

```

SUBROUTINE ITER (T,X)
10 T1=T
T=EXP((X+.2475*LOG(T)-CP1(T))/).2475)
IF(ABS(T-T1) .LT. 1.E-2) GO TO 20
GO TO 10
20 RETURN
END
SUBROUTINE ITER2(T,X)
10 T1=T
T=X/ACP(T)
IF(ABS(T-T1) .LT. 1.E-2) GO TO 20
GO TO 10
20 RETURN
END

```

```

SUBROUTINE HEATER (QB, T1H, T7H, NCPH, NTPH, PHI, T3, T4)
REAL LHV, NH, MF, MA, NCPH, NTPH, N
COMMON /HTR/NH, PRH, DPPH, T2H, T3H, T4H, T5H, T6H, MA, MF
LHV=12900.
FA=.0922
H7H=ACP(T7H)*T7H
H1H=ACP(T1H)*T1H
NH=1-(((1+FA*PHI)*H7H-H1H)/(FA*PHI*LHV))
MF=QB/(NH*LHV)
MA=MF/(FA*PHI)
T2H=0.0
T6H=0.0
10 CPT=ACP((T6H+T7H)/2.)
CPC=ACP((T1H+T2H)/2.)
N=(1-FA*PHI)*CPT*NTPH*(CPT*T7H-CPC*T1H)
D=CPC*T1H*(CPC/NCPH-CPT*NTPH)
PRH=(N/D)**(NCPH/CPC)
TH2=T1H*PRH**(CPC/NCPH)
N=(1+FA*PHI)*CPT*T7H+CPC*T1H*(PRH**(CPC/NCPH)-1)
D=(1+FA*PHI)*CPT*T7H*PRH**(CPT/NTPH)
DPPH=1-(N/D)**(1./(CPT*NTPH))
TRH=(1-DPPH)*PRH
TH6=T7H*(TRH)**(CPT*NTPH)
IF(ABS(T2H-TH2) .LT. .1) GO TO 20
IF(ABS(T6H-TH6) .LT. .1) GO TO 20
T2H=TH2
T6H=TH6
GO TO 10
20 T2H=TH2
T5H=TH6
T5H=T3+100.
T4H=T5H+QB/(ACP(T5H/2+1300.)*(MA+MF))
T3H=T2H+(1+MF/MA)*(T5H-T6H)
RETURN
END
SUBROUTINE DHD(PR)
COMMON /DIA/DHDREG, DHDCLR, DHDHTR, DHDREC
DHDREG=.557+.0933*PR
IF(DHDREG .GT. .95) DHDREG=.95
DHDCLR=.076+.092*PR
DHDHTR=.214+.048*PR
DHDREC=.65
RETURN
END
SUBROUTINE DPP(T6, T7, PR, DP, ER, T2, T3, DPPH, TH4, TH5, T4, PRH, P, M, MA
*, MF, K)
REAL M, MA, MF, M1, M2
COMMON /PRES/DPPWHB, DPPREG, DPCLR, DPPREC, DPH1, DPH2, DHDHT

```

```

DTG=T6-T7
DPPWHB=FLOAT(K)*.002
DPPREG=(.135-.0284*PR)*DP/.1
IF(DPPREG.LT..01) DPPREG=.01
IF(T2.EQ.T3) DPPREG=0.0
DPH2=(.0108*PR-.01)*DP/.1
T1=(T3+T4)*.5
TT=(TH4+TH5)*.5
P1=P*(PR-OP)
P2=14.7*(PRH-DPPH)
M1=M
M2=MA+MF
XMU1=AMU(T1)
XMU2=AMU(TT)
XRHO1=ARHO(T1,P1)
XRHO2=ARHO(TT,P2)
B=(M1/M2)**(-1.75)*(XMU1/XMU2)**(-.25)*(XRHO1/XRHO2)*(P1/P2)
DPH1=DPH2*DHDHT**3/B
DPPCLR=OP-DPPWHB-DPPREG-DPH1
DPPREC=DPPH-DPH2-.1
RETURN
END

```

```

SUBROUTINE TURBVOL (G,M,V,TR,T,VOL)
REAL M,N,KI1,IT
SF=4.0
UT=850.
PHIT=0.6
VA=0.9
CL=2.0
PI=3.14159
RHOM=15.12
A=9.63E6
B=-95.14
ALPHA=1.2
A1=2.5
X1=.307
KI1=3.39E-3
THETA=0.8
RT=SQRT(M*V/(PHIT*UT*PI*(1.-VA**2)))
VB=SQRT(1.-TR**(1./G)*(1.-VA**2))
C1=0.2*(A1+1.)*1./V*(1.-VA**2)*UT**2*RT**2*X1/KI1
C2=2.*(A-B*T)/(SF*ALPHA)
C3=2.*B*T*(1.-VA**2)**(G-1.)/(SF*ALPHA)
C4=-1.*THETA*RHOM*UT**2/2.
H=(VA-VB)/20.
SUM=0.0
X1=0.0
Y1=VA
DO 100 J=1,21
  N=C1*((1.-Y1)/(1.+Y1))*PHIT**2+Y1**2

```

```

      D=C2+C3*(1.-Y1**2)**(1.-G)-C4*(1.-Y1**2)
      DN=C1*(2.*Y1*(1.-Y1)/(1.-Y1)-(PHIT**2+Y1**2)/(1.-Y1)-(1.-Y1)
***(-2)*(1.-Y1)*(PHIT**2+Y1**2))
      DD=2.*Y1*(1.-Y1**2)**(-1.*G)*(G-1.)*C3-2.*Y1*C4
      X2=.5*(1./(N/D)**.5)*((DN*D-DD*N)/D**2)
      IF(X1 .EQ. 0.0) GO TO 50
      SUM=SUM+(X1+X2)/2.
50      X1=X2
      Y1=Y1-H
100     CONTINUE
      IT=H*SUM
      VOL=2.*PI*RT**2*CL*IT
      RETURN
      END

```

SUBROUTINE COMPVOL (G,M,V,PR,VOL)

REAL M,N,KI1,IT

SF=4.0

UT=850.

PHIT=0.5

VA=0.6

CL=2.0

PI=3.14159

RHOM=15.12

ALPHA=1.2

A1=12.0

X1=.05

KI1=4.93E-5

THETA=0.8

SIGMAY=12.54E6

RT=SQRT(M\*V/(PHIT\*UT\*PI\*(1.-VA\*\*2)))

VB=SQRT(1.-PR\*\*(-1./G)\*(1.-VA\*\*2))

C1=.2\*(A1+1.)\*1./V\*(1.-VA\*\*2)\*UT\*\*2\*RT\*\*2\*PHIT\*\*2\*X1/KI1

C2=-1\*THETA\*RHOM\*UT\*\*2/2.

C3=2.\*SIGMAY/(SF\*ALPHA)

H=(VB-VA)/20.

SUM=0.0

X1=0.0

Y1=VA

DO 100 J=1,21

N=C1\*((1.-Y1)/(1.+Y1))\*(PHIT\*\*2+.49\*Y1\*\*2)/(PHIT\*\*2+.7225\*Y1\*\*2

\*)

D=C3+C2\*(1.-Y1\*\*2)

DN=C1\*(-1.\*(PHIT\*\*2+.49\*Y1\*\*2)/(PHIT\*\*2+.7225\*Y1\*\*2)\*(1.+Y1)-(1

\*.-Y1)\*(1.+Y1)\*\*(-2)\*(PHIT\*\*2+.49\*Y1\*\*2)/(PHIT\*\*2+.7225\*Y1\*\*2)+

\*.98\*Y1\*(1.-Y1)/(1.+Y1)/(PHIT\*\*2+.7225\*Y1\*\*2)-1.445\*Y1\*(1.-Y1)/

\*(1.+Y1)\*(PHIT\*\*2+.49\*Y1\*\*2)\*(PHIT\*\*2+.7225\*Y1\*\*2)\*\*(-2))

DD=-2.\*C2\*Y1

X2=.5\*(1./(N/D)\*\*.5)\*((DN\*D-DD\*N)/D\*\*2)

IF(X1 .EQ. 0.0) GO TO 50

SUM=SUM+(X1+X2)/2.

```

50  X1=X2
    Y1=Y1+H
100 CONTINUE
    IT=-H*SUM
    VOL=2.*PI*RT**2*CL*IT
    RETURN
    END

```

```

SUBROUTINE REGEN (T2,T3,T5,T6,P,D,MB,PR,DPPREG,DHDREG,VOL)
REAL MB
T=T5/2+T6/2
P1=P*PR
SIGMA=ASIGMA(T,P1)
IF(T2 .EQ. T3) GO TO 99
DTLM=T3-T2
GAMMA=1./(6803.*P)**.41*(.0254*D)**1.18/(.56*DTLM)**1.41
DH1=CP2(T5)-CP2(T6)
PI=3.14159
AREG=PI/4.*SIGMA*GAMMA*(MB*.454)*(DH1*2326.)**1.41*(1.+DHDREG)
***2.41*(1.+PR**(+2)*DHDREG**(-3))**.41*35.3
VOL=AREG*DPPREG**(-.41)
99  RETURN
    END

```

```

SUBROUTINE RECUP (T2H,T3H,T5H,T6H,PRH,DPPH,D,MA,MF,DPPREC,VOL)
REAL MA,MF
T=T5H/2.+T6H/2.
PC=1./(1.-DPPH)
P=14.7*PRH
SIGMA=ASIGMA(T,P)
DTLM=T3H-T2H
GAMMA=(6803.*P)**(-.41)*(0.0254*D)**1.18*(.56*DTLM)**(-1.41)
DH1=CP2(T5H)-CP2(T6H)
PI=3.14159
DHDREC=.65
CM=MA+MF
AREC=PI/4.*SIGMA*GAMMA*(CM*.454)*(DH1*2326.)**1.41*(1.+DHDREC)
***2.41*(1.+DHDREC**(-3)*PC**2)**.41*35.3
VOL=AREC*DPPREC**(-.41)
RETURN
END

```

```

SUBROUTINE COOLER (T7,T1,P,D,NTP,MB,DHDCLR,DPPCLR,VOL)
REAL NPP,NTP,MB
IF(T7 .LT. T1) GO TO 99
TA=T7/2.+T1/2.
SIGMA=ASIGMA(TA,P)
TC1=530.
TC2=540.
DTLM=(T1-TC1-T7+TC2)/LOG((T1-TC1)/(T7-TC2))
GAMMA=(6803.*P)**(-.41)*(0.0254*D)**1.18*(.56*DTLM)**(-1.41)

```

```

DH1=CP2(T7)-CP2(T1)
PI=3.14159
TW=TC1/2.+TC2/2.
RK=AK(TA,P)/1.E-4
RMU=AMU(TA)/6.4E-4
RM=(T7-T1)*ACP(TA)/(1.*10.)
RPR=APR(TA,P)/6.4
NPP=.80
RRHO=ARHO(TA,P)/64.0
RSV=ARHO(T7,P)/64.0
ALPHA=RK*RMU**(-.8)*RM**.8*RPR**.4
CB=RM**(-2.75)*RMU**(-.25)*RRHO*RSV/NTP/NPP
ACLR=PI/4.*SIGMA*GAMMA*(MB*.454)*(DH1*2326.)**1.41*(1.-DHDCLR)
**1.41*(1.+ALPHA*DHDCLR)**1.41*(1.+CB*DHDCLR**(-3))**.41*35.3
VOL=ACLR*DPCLR**(-.41)
99 RETURN
END

```

```

SUBROUTINE COMBUSTOR (T3,T4,T4H,T5H,WP,PR,D,MB,PRH,MA,MF,VOL)
REAL MB,MA,MF,M
COMMON /COMB/DPPRG,DPPRC,DPPHE,DHDHR,DPHEZ
T=T3/2+T4/2
P=WP*(PR-DPPRG)
SIGMA=ASIGMA(T,P)
DTLM=(T5H-T3-T4H+T4)/LOG((T5H-T3)/(T4H-T4))
GAMMA=(6803.*P)**(-.41)*(.0254*D)**1.19*(.56*DTLM)**(-1.41)
DH1=CP2(T4)-CP2(T3)
PI=3.14159
TH=T4H/2+T5H/2
TRH=(1.-DPPHE)*PRH
PH=14.7*(PRH-DPPRC)
RK=AK(T,P)/AK(TH,PH)
RMU=AMU(T)/AMU(TH)
M=MA+MF
RM=MB/M
RPR=APR(T,P)/APR(TH,PH)
ALPHA=RK*RMU**(-.8)*RM**.8*RPR**.4
AHTR=PI/4.*SIGMA*GAMMA*(MB*.454)*(DH1*2326.)**1.41*(1.+DHDHR)*
*(1.+ALPHA*DHDHR)**1.41*DHDHR**(-1.23)*35.3
VOL=AHTR*DPHEZ**(-.41)
RETURN
END

```

```

SUBROUTINE WHBVOL (MB,MS,T6,T7,NWHB,H2S,H3S,DPPWHB,VOL)
REAL MB,MS,NWHB,NTU
T=T6/2+T7/2
CP=ACP(T)
CPS=2.0
CR=MS*CPS/(MB*CP)
IF(CR.GT.1.) GO TO 10
CMIN=MS*CPS

```

```

GO TO 20
10 CR=1./CR
   CMIN=CP*MB
20 PS=4.0
   ER=(NWHB*CR-1.)/(NWHB-1.)
   NTU=(-PS)*LOG(1.+1./CR*LOG(1.-CR*(1.-ER**(1./PS)))/(CR-ER**(1./
*PS))))
   DH=H3S-H2S
   VOL=.00045*CMIN*NTU*MS*DH*DPPNHB**(-.41)
   RETURN
   END

```

```

SUBROUTINE CONDVOL (MS,X,VOL)
REAL MS
VOL=MS*X**27.3
RETURN
END

```

SUBROUTINE STMTAB (NI,XI,II)

DIMENSION SATLIQ(3),STEAM(3),COEFFT(237)

COMMON /STM/PRESS,TEMP,QUAL,SATLIQ,STEAM

DATA (COEFFT(I),I=1,30) / .22082221E+04, .55000000E-03

\* , .69573391E+03, .60464261E+01, .70000000E+01, .13552680E-00  
\* , -.19513682E+00, -.52279952E-00, .91148958E-01, .61343682E-01  
\* , -.50625849E+00, .72595720E+00, .14585694E+02, .12404319E-03  
\* , .55592942E-03, .20000000E+01, -.74133440E-06, .73324823E-06  
\* , .26548914E-04, .91349306E-04, .15679922E-02, .25032530E-01  
\* , .30706919E+00, .36241343E+01, .44960616E+02, .17926732E-03  
\* , .45000000E+03, .55000000E+03, -.98736888E-22, .19301230E-19/

DATA (COEFFT(I),I= 31, 60) / .30041189E-17, -.42113669E-15

\* , -.32893178E-14, -.11734466E-11, .11244475E-07, -.73419653E-05  
\* , .81536841E-02, .69519265E-01, .25000000E+03, .20575548E-23  
\* , -.64272696E-21, .12704366E-18, -.96976163E-15, .63370000E-13  
\* , -.54251564E-10, .44797322E-07, -.23104756E-04, .17490541E-01  
\* , .33953897E+01, .43010158E+03, .54927377E+03, -.12444779E-19  
\* , .92756543E-17, -.95470656E-15, -.29004677E-12, .35353292E-10  
\* , .39936598E-08, -.99567313E-06, -.59157992E-03, .78143274E-00/

DATA (COEFFT(I),I= 61, 90) / .55000000E+03, .21848036E+03

\* , -.14722587E-21, .56553573E-19, .47725605E-17, -.53349163E-14  
\* , .27455505E-12, -.18335302E-10, -.31160333E-06, -.11956354E-03  
\* , .98512754E+00, .25000000E+03, .47000000E+03, .55000000E+03  
\* , .73857180E-22, .33225506E-19, .30075575E-18, -.73898651E-15  
\* , -.70679233E-14, .90114201E-11, .58149642E-09, .86712981E-07  
\* , .30734203E-04, .21762691E-01, .25000000E+03, -.78459129E-25  
\* , -.33608032E-23, .95319792E-20, .25729365E-18, -.31591904E-15/

DATA (COEFFT(I),I= 91,120) / .60506309E-13, .13684599E-10

\* , .15587770E-07, .81264440E-05, .17002639E-01, .45000000E+03  
\* , .55000000E+03, .94743147E-18, .24971478E-16, -.38302588E-14  
\* , .44979672E-12, -.51337380E-10, .49178986E-08, .48326895E-05  
\* , .12399614E-02, .12798551E+01, .54927377E+03, .25000000E+03  
\* , .12945371E-21, -.65873139E-19, -.13817574E-17, .62520106E-14  
\* , .17548001E-12, .23202424E-09, .36145967E-06, .12506461E-03  
\* , .10150974E+01, .21848036E+03, .45000000E+03, .55000000E+03/

DATA (COEFFT(I),I=121,150) /-.21134438E-20, .15327038E-18

\* , .69217855E-16, -.18345822E-14, -.66417458E-12, .14589563E-10  
\* , .59598410E-08, .45575915E-06, .12325099E-02, .74969797E+00  
\* , .25000000E+03, .50084539E-23, -.15659070E-21, -.46099119E-18  
\* , .49239634E-17, .16250351E-13, -.74068320E-12, .10479899E-08  
\* , -.85546496E-06, .14285709E-02, .36753405E+00, .17000000E+01  
\* , .19000000E+01, -.11085077E+05, -.15994587E+05, .91407688E+04  
\* , -.18796109E+03, .15699797E+03, -.20213342E+03, -.48650175E+02/

DATA (COEFFT(I),I=151,180) / .15040455E+03, -.13050547E+03

\* , .11199490E+04, .15000000E+01, -.14863585E+06, -.13414819E+06  
\* , .62379937E+05, .29474498E+05, -.18907586E+05, -.57858876E-03  
\* , .35122466E+04, -.12340833E+04, -.68929827E+02, .12036836E+04  
\* , .30000000E+01, .13000000E-04, .70848990E+01, .16507788E-02  
\* , .52122736E+03, -.11682947E-01, -.12001588E+00, .20411991E+01  
\* , .12340954E-04, .13555136E-03, -.15099319E-03, .30000000E-01  
\* , .18000000E+01, .23822091E+02, .18776649E+03, .33080504E-03/

```

DATA (COEFFT(I),I=181,210) /-.32141408E+01, .42449101E-03
*, .16400835E+04, .18746657E+02, .53978878E+02, .20719841E-04
*, .13000000E+04, .13000000E+01, -.64369800E-05, .96418803E-02
*, .38879248E+01, .11034060E-05, .47225001E-03, -.94113600E-01
*, .69416973E-05, -.60892120E-02, .10951922E+01, .13000000E-04
*, .18000000E+01, -.33101208E-03, .21561916E+01, .53500291E-03
*, -.77236618E-03, .36753650E+00, -.25450121E+03, .25249707E-02
*, -.16427106E+01, .61477766E+03, 0.0, 0.0
DATA (COEFFT(I),I=211,237) / 0.0, 0.0, 0.0, 0.0, 0.0
*, 0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0, .90000000E-03
*, .14000000E+01, -.15478259E-04, .19351556E-01, .24698909E-01
*, .23329644E-04, .11493791E-02, -.13139208E+02, .52860219E-05
*, -.12592899E-01, .55101160E+01/
N=NI
X=XI
Y=YI
I=N-3
LINK=0
PRESS=X
DELTA1=0.0
ERROR1=0.0
ERROR2=0.0
IF (N-6) 1000,1000,1030
1000 IF (I) 1020,1020,1010
1010 LINK=1
N=I
1020 IF (X-COEFFT(N)) 1040,1040,1520
1030 N=I
1040 GO TO (1130,1060,1190,1230,1080,1090,1180,1330),N
1050 X=Z
N=2
1060 TEMP=X
GO TO 1190
1070 PRESS=EXP(Z)
GO TO 1150
1080 II=2
JJ=3
TOLER=.005
GO TO 1100
1090 II=3
JJ=2
TOLER=.000005
1100 H=Y
1110 LINK=2
1120 N=1
1130 X=ALOG(PRESS)
PLOG=X
GO TO 1190
1140 TEMP=Z
1150 X=TEMP
J=1

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N=4
GO TO 1190
1160 SATLIQ(J)=Z
      J=J+1
      N=N+1
      IF (J-3) 1190,1190,1170
1170 IF (LINK) 1640,1640,1300
1180 H=X
      S=Y
      X=S
1190 I=23*N-19
      K=1
      IF (X-COEFFT(I)) 1200,1200,1210
1200 K=12
1210 I=I-K
      ARG=X-COEFFT(I)
      Z=0.0
      DO 1220 K=1,10
      I=I+1
1220 Z=Z*ARG+COEFFT(I)
      GO TO (1140,1070,1050,1160,1160,1160,1410),N
1230 TEMP=Y
      GO TO 1300
1240 ERROR=H-STEAM(I)
      IF (ABS(ERROR)-TOLER) 1640,1250,1250
1250 IF (ERROR1) 1260,1280,1260
1260 ERROR1=ERROR1-ERROR
      IF (ABS(ERROR1)-TOLER) 1290,1290,1270
1270 SLOPE=DELTA1/ERROR1
1280 DELTA1=SLOPE*ERROR
      ERROR1=ERROR
1290 TEMP=TEMP+DELTA1
1300 IF (PRESS-COEFFT(1)) 1320,1320,1310
1310 IF ((.00001178*PRESS+.09411)*PRESS+382.1-TEMP) 1320,1320,1620
1320 T=.55555556*TEMP+255.38223
      TLOG=ALOG(T)
      TAU=1.0/T
      COEFFT(222)=TAU*TAU*196210.06
      COEFFT(217)=EXP(COEFFT(222)+7.8791476-TLOG)
      COEFFT(221)=162460.*TAU
      COEFFT(220)=125970.*TAU
      COEFFT(219)=EXP(149.27765-23.*TLOG)
      COEFFT(212)=1.39-COEFFT(217)
      COEFFT(211)=82.546-COEFFT(221)
      COEFFT(210)=.21828*T-COEFFT(220)
      COEFFT(209)=COEFFT(219)-.0003635*T
      COEFFT(222)=(COEFFT(222)+COEFFT(222)+1.0)*COEFFT(217)
      COEFFT(217)=COEFFT(212)-COEFFT(222)
      COEFFT(214)=COEFFT(217)/COEFFT(212)
      COEFFT(216)=COEFFT(211)*COEFFT(214)+41.273-COEFFT(221)
      COEFFT(215)=COEFFT(210)*COEFFT(214)-.5*COEFFT(220)

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COEFFT(214)=COEFFT(209)*COEFFT(214)+1.8461538*COEFFT(219)
COEFFT(221)=.50*COEFFT(211)-COEFFT(216)
COEFFT(220)=.25*COEFFT(210)-COEFFT(215)
COEFFT(219)=.076923077*COEFFT(209)-COEFFT(214)
COEFFT(218)=(.0037299965*T+14.531813)*T+17906.513+472.2493*TLOG
COEFFT(223)=-.0074599931*T-14.531813*TLOG+2.4624439+472.24937
**TAU
1330 P=.068046190*PRESS
PLOG=ALOG(PRESS)
COEFFT(213)=COEFFT(212)*TAU
COEFFT(226)=COEFFT(213)*P
COEFFT(225)=COEFFT(226)*COEFFT(226)
COEFFT(224)=COEFFT(225)*COEFFT(225)
COEFFT(224)=COEFFT(224)*COEFFT(224)*COEFFT(226)
COEFFT(226)=COEFFT(226)*COEFFT(213)
COEFFT(213)=P*TAU
STEAM(1)=(((COEFFT(209)*COEFFT(224)+COEFFT(210))*COEFFT(225)+
*COEFFT(211))*COEFFT(226)+COEFFT(212)+4.55504/COEFFT(213))
**0160185
STEAM(2)=((((COEFFT(214)*COEFFT(224)+COEFFT(215))*COEFFT(225)+
*COEFFT(216))*COEFFT(226)+COEFFT(217))*P+COEFFT(218))*04355685
STEAM(3)=((((COEFFT(219)*COEFFT(224)+COEFFT(220))*COEFFT(225)+
*COEFFT(221))*COEFFT(226)+COEFFT(222))*COEFFT(213)+COEFFT(223)
*+4.55504*PLOG)*(-.02419825)
QUAL=1.0
I=LINK+1
GO TO (1640,1640,1340,1240,1340,1450),I
1340 X=STEAM(II)
IF (H-X) 1350,1640,1360
1350 Y=SATLIQ(II)
QUAL=(H-Y)/(X-Y)
X=1.0-QUAL
STEAM(I)=QUAL*STEAM(I)+X*SATLIQ(I)
STEAM(JJ)=QUAL*STEAM(JJ)+X*SATLIQ(JJ)
STEAM(II)=H
IF (LINK-2) 1640,1640,1460
1360 I=(II-1)*11+154
J=1
X=PLOG
1370 00 1380 K=209,219
COEFFT(K)=COEFFT(I)
1380 I=I+1
X=X-COEFFT(209)
Y=Y-COEFFT(210)
COEFFT(209)=(COEFFT(211)*X+COEFFT(212))*X+COEFFT(213)
COEFFT(210)=(COEFFT(214)*X+COEFFT(215))*X+COEFFT(216)
COEFFT(211)=((COEFFT(217)*X+COEFFT(218))*X+COEFFT(219))*Y
Z=COEFFT(211)+COEFFT(210)
SLOPE=COEFFT(211)+Z
Z=Z*Y+COEFFT(209)
GO TO (1390,1430,1530,1540),J

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1390 LINK=3
      IF (Z-TEMP) 1300,1300,1400
1400 TEMP=Z
      GO TO 1300
1410 J=2
      I=227
      X=H
      IF (Z-H) 1420,1370,1370
1420 I=187
      GO TO 1370
1430 DPDS=SLOPE
      PRESS=EXP(Z)
      PLOG=Z
      IF (I-227) 1520,1520,1440
1440 LINK=4
      II=2
      JJ=3
      GO TO 1120
1450 DH=H-STEAM(2)
      STEAM(3)=STEAM(3)-DH/(TEMP+459.69)
1460 DS=S-STEAM(3)
      DELTA1=STEAM(3)-ERROR1
      IF (ERROR1) 1470,1490,1470
1470 IF (ABS(DELTA1)-.000005) 1500,1500,1480
1480 DPDS=(PLOG-PLOG1)/DELTA1
1490 PLOG1=PLOG
      ERROR1=STEAM(3)
1500 PRESS=PRESS*(1.0+DS*DPDS)
      IF (LINK-4) 1510,1510,1550
1510 IF (ABS(DS)-.000005) 1140,1120,1120
1520 LINK=5
      X=H
      Y=S
      I=198
      J=3
      GO TO 1370
1530 TEMP=Z
      DTDS=SLOPE
      X=PLOG
      Y=H
      I=165
      J=4
      GO TO 1370
1540 DTDH=SLOPE
      GO TO 1300
1550 TEMP=TEMP+DS*DTDS
      IF (ABS(DH)-.005) 1610,1560,1560
1560 DELTA2=DH-ERROR2
      IF (ERROR2) 1570,1590,1570
1570 IF (ABS(DELTA2)-.005) 1600,1600,1580
1580 DTDH=(TEMP1-TEMP)/DELTA2

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1590 TEMP1=TEMP
      ERROR2=0H
1600 TEMP=TEMP+DH*DTDH
      GO TO 1320
1610 IF (ABS(DS)-.000005) 1640,1500,1500
1620 WRITE (6,1630) NI,XI,YI
1630 FORMAT (I3,2E14.3,13H OUT OF RANGE)
      STOP
1640 RETURN
      END
```

APPENDIX B

BRAYTON CYCLE: PRESSURE RATIO=2.00  
 WORKING PRESSURE=135.0  
 TOTAL PRESSURE DROP=.10  
 MASS FLOW (Lbm/s)=444.37

STATE	TEMP(deg R)	SUMMARY: THERMAL EFF=0.370		
1	540.0	HEATER EFF=0.933 (PHI=0.90)		
2	675.7	SFC (Lbm/HP-hr)=0.572		
3	1668.3	VOL TOTAL(cu ft)=516.5		
4	2060.0	POWER(HP)=25000.0		
5	1804.2	WCRK FRAC BY STM CYCLE=0.045		
6	311.2			
PP	784.0			
7	778.3			
COMPONENT	DPP	DHD	VOL(cu ft)	
REGEN	.078	.744	15.5	EFF=0.88
TURBINE			10.0	EFF(P)=0.91
COOLER	.007	.260	139.3	
COMPRESSOR			29.3	EFF(P)=0.88
HEATER	.0005			
BOILER	.014			EFF=0.94

HEATER CYCLE: PRESSURE RATIO = 4.79  
 TOTAL PRESSURE DROP=.43  
 AIR FLOW(Lbm/s)=47.84  
 FUEL FLOW(Lbm/s)= 3.97

STATE	TEMP(deg R)			
1h	535.0			
2h	835.2			
3h	1727.4			
4h	5054.5			
5h	1768.8			
6h	945.0			
7h	760.0			
COMPONENT	DPP	DHD	VOL(cu ft)	
RECUP	.321	.650	2.6	EFF=0.96
TURBINE			1.1	
HEATER	.012	.310	67.4	
COMPRESSOR			16.0	EFF(P)=0.35

RANKINE CYCLE: SATURATION PRESSURE= 56.7  
 STEAM FLOW(Lbm/s)= 2.96  
 FLOW RATIO=0.0067

STATE	TEMP(deg R)	PRESSURE(psi)	
1s	540.0	0.5	
2s	555.0	56.7	
SP	749.0	56.7	
3s	776.2	56.7	
4s	540.0	0.5	QUAL=0.844
COMPONENT	VOL(cu ft)		
BOILER	162.3		
TURBINE	4.3	EFF(IS)=0.88	
CONDENSER	68.3		

BRAYTON CYCLE: PRESSURE RATIO= 3.00  
 WORKING PRESSURE =135.0  
 TOTAL PRESSURE DROP=.10  
 MASS FLOW(Lbm/s)=287.63

STATE	TEMP(deg R)	SUMMARY: THERMAL EFF=0.432		
1	540.0	HEATER EFF=0.933 (PHI=0.90)		
2	769.3	SFC(Lbm/HP-hr)=0.490		
3	1538.3	VOL TOTAL(cu ft)= 318.1		
4	2060.0	POWER(HP)=25000.0		
5	1643.6	WORK FRAC BY STEAM CYCLE=0.044		
6	874.7			
7P	841.2			
7	831.8			
COMPONENT	DPP	DHD	VOL(cu ft)	
REGEN	.050	.837	11.5	EFF=0.88
TURBINE			5.3	EFF(P)=0.91
COOLER	.024	.352	88.9	
COMPRESSOR			20.9	EFF(P)=0.88
HEATER	.0004			
BOILER	.026			EFF=0.94

HEATER CYCLE: PRESSURE RATIO= 4.79  
 TOTAL PRESSURE DROP=.43  
 AIR FLOW(Lbm/s)= 40.99  
 FUEL FLOW(Lbm/s)= 3.40

STATE	TEMP(deg R)			
1h	535.0			
2h	835.2			
3h	1586.5			
4h	4932.9			
5h	1638.8			
6h	945.0			
7h	760.0			
COMPONENT	DPP	DHD	VOL(cu ft)	
RECUP	.310	.650	2.2	EFF=0.93
TURBINE			0.9	EFF(P)=0.89
HEATER	.022	.358	28.6	
COMPRESSOR			12.7	EFF(P)=0.85

RANKINE CYCLE: SATURATION PRESSURE= 128.0  
 STEAM FLOW(Lbm/s)= 2.48  
 FLOW RATIO=0.0086

STATE	TEMP(deg R)	PRESSURE(psi)	
1s	540.0	0.5	
2s	555.0	128.0	
SF	806.2	128.0	
3s	839.7	128.0	
4s	540.0	0.5	QUAL=0.819
COMPONENT	VOL(cu ft)		
BOILER	88.3		
TURBINE	3.4	EFF(1S)=0.88	
CONDENSER	55.5		

BRAYTON CYCLE: PRESSURE RATIO= 4.00  
 WORKING PRESSURE = 135.0  
 TOTAL PRESSURE DROP=.10  
 MASS FLOW (Lbm/s)=239.91

STATE	TEMP(deg R)	SUMMARY: THERMAL EFF=0.487	
1	540.0	HEATER EFF=0.933 (PHI=0.90)	
2	843.9	SFC(Lbm/HP-hr)=0.473	
3	1453.3	VOL TOTAL(cu ft)= 352.2	
4	2060.0	POWER(HP)=25000.0	
5	1536.9	WORK FRAC BY STM CYCLE=0.063	
6	927.0		
PP	876.3		
7	860.6		
COMPONENT	DPP	DHD	VOL(cu ft)
REGEN	.021	.930	13.2 EFF=0.88
TURBINE			3.6 EFF(P)=0.91
COOLER	.032	.451	39.8
COMPRESSOR			12.4 EFF(P)=0.88
HEATER	.0003		
BOILER	.046		EFF=0.94

HEATER CYCLE: PRESSURE RATIO= 4.79  
 TOTAL PRESSURE DROP=.43  
 AIR FLOW(Lbm/s)=39.59  
 FUEL FLOW(Lbm/s)= 3.29

STATE	TEMP(deg R)	SUMMARY: THERMAL EFF=0.487	
1h	535.0	HEATER EFF=0.933 (PHI=0.90)	
2h	835.2	SFC(Lbm/HP-hr)=0.473	
3h	1494.5	VOL TOTAL(cu ft)= 352.2	
4h	4855.0	POWER(HP)=25000.0	
5h	1553.8	WORK FRAC BY STM CYCLE=0.063	
6h	945.0		
7h	760.0		
COMPONENT	DPP	DHD	VOL(cu ft)
RECUP	.299	.650	2.1 EFF=0.92
TURBINE			0.8 EFF(P)=0.89
HEATER	.033	.406	17.7
COMPRESSOR			12.0 EFF(P)=0.85

RANKINE CYCLE: SATURATION PRESSURE= 199.9  
 STEAM FLOW(Lbm/s)= 3.19  
 FLOW RATIO=0.0133

STATE	TEMP(deg R)	PRESSURE(psi)	
1s	540.0	0.5	
2s	555.0	199.9	
SF	841.8	199.9	
3s	892.0	199.9	
4s	540.0	0.5	QUAL=0.810
COMPONENT	VOL(cu ft)		
BOILER	119.0		
TURBINE	5.1	EFF(IS)=0.88	
CONDENSER	70.5		

BRAYTON CYCLE: PRESSURE RATIO= 5.00  
 WORKING PRESSURE=135.0  
 TOTAL PRESSURE DROP=.10  
 MASS FLOW (Lbm/s)=212.34

STATE	TEMP(deg R)
1	540.0
2	905.8
3	1391.3
4	2060.0
5	1458.1
6	972.1
PP	376.8
7	846.9

SUMMARY: THERMAL EFF=0.460  
 HEATER EFF=0.933 (PHI=0.90)  
 SFC(Lbm/HP-hr)=0.460  
 VOL TOTAL(cu ft)=596.1  
 POWER(HP)=25000.0  
 WORK FRAC BY STM CYCLE=0.111

COMPONENT	DPP	DHD	VOL(cu ft)	
REGEN	.010	.950	15.7	EFF=0.88
TURBINE			2.7	EFF(P)=0.91
COOLER	.022	.536	107.8	
COMPRESSOR			16.7	EFF(P)=0.88
HEATER	.0003			
BOILER	.068			EFF=0.94

HEATER CYCLE: PRESSURE RATIO= 4.79  
 TOTAL PRESSURE DROP=.43  
 AIR FLOW(Lbm/s)= 38.49  
 FUEL FLOW(Lbm/s)= 3.19

STATE	TEMP(deg R)
1h	535.0
2h	335.2
3h	1427.4
4h	4798.9
5h	1491.3
6h	945.0
7h	760.0

COMPONENT	DPP	DHD	VOL(cu ft)	
RECUP	.289	.650	2.1	EFF=0.90
TURBINE			0.8	EFF(P)=0.89
HEATER	.044	.454	12.4	
COMPRESSOR			11.5	EFF(P)=0.85

RANKINE CYCLE: SATURATION PRESSURE= 200.0  
 STEAM FLOW(Lbm/s)= 5.21  
 FLOW RATIO=0.0245

STATE	TEMP(deg R)	PRESSURE(psi)	
1s	540.0	0.5	
2s	555.0	200.0	
SF	841.3	200.0	
3s	937.1	200.0	
4s	540.0	0.5	QUAL=0.826

COMPONENT	VOL(cu ft)	
BOILER	298.1	
TURBINE	10.9	EFF(IS)=0.88
CONDENSER	117.4	

BRAYTON CYCLE: PRESSURE RATIO = 6.00  
 WORKING PRESSURE=135.0  
 TOTAL PRESSURE DRCP=.10  
 MASS FLOW(Lbm/s)=197.00

STATE	TEMP(deg R)
1	540.0
2	959.4
3	1343.8
4	2060.0
5	1396.2
6	1011.8
33	376.8
7	335.3

SUMMARY: THERMAL EFF=0.464  
 HEATER EFF=0.933 (PHI=0.90)  
 SFC(Lbm/HP-hr)=0.456  
 VOL TOTAL(cu ft)=879.0  
 POWER(HP)=25000.0  
 WORK FRAC BY STM CYCLE=0.151

COMPONENT	DPP	DHD	VOL(cu ft)	EFF
REGEN	.010	.950	14.4	EFF=0.88
TURBINE			2.2	EFF(P)=0.91
COOLER	.016	.628	129.7	
COMPRESSOR			15.8	EFF(P)=0.88
HEATER	.0003			
BOILER	.074			EFF=0.94

HEATER CYCLE: PRESSURE RATIO= 4.79  
 TOTAL PRESSURE DROP=.43  
 AIR FLOW(Lbm/s)=38.17  
 FUEL FLOW(Lbm/s)- 3.17

STATE	TEMP(deg R)
1h	535.0
2h	835.2
3h	1375.4
4h	4755.8
5h	1443.8
6h	945.0
7h	760.0

COMPONENT	DPP	DHD	VOL(cu ft)	EFF
RECUP	.278	.650	2.1	EFF=0.89
TURBINE			0.8	EFF(P)=0.89
HEATER	.055	.502	9.5	
COMPRESSOR			11.4	EFF(P)=0.85

RANKINE CYCLE: SATURATION PRESSURE= 200.0  
 STEAM FLOW(Lbm/s)= 6.70  
 FLOW RATIO=0.0340

STATE	TEMP(deg R)	PRESSURE(psi)
1s	540.0	0.5
2s	555.0	200.0
SF	841.8	200.0
3s	976.8	200.0
4s	540.0	0.5

QUAL=0.838

COMPONENT	VOL(cu ft)	EFF
BOILER	523.6	
TURBINE	16.2	EFF(1S)=0.88
CONDENSER	153.3	

BRAYTON CYCLE: PRESSURE RATIO=7.00  
 WORKING PRESSURE=135.0  
 TOTAL PRESSURE DROP=.10  
 MASS FLOW(Lbm/s)=187.48

STATE	TEMP(deg R)	SUMMARY: THERMAL EFF=0.463	
1	540.0	HEATER EFF=0.933 (PHI=0.90)	
2	1007.0	SFC(Lbm/HP=hr)=0.457	
3	1304.9	VOL TOTAL(cu ft)=1195.7	
4	2060.0	POWER(HP)=25000.0	
5	1345.5	WORK FRAC BY STM CYCLE=0.189	
6	1047.6		
PP	876.8		
7	825.2		
COMPONENT	DPP	DHD	VOL(cu ft)
REGEN	.010	.950	13.6 EFF=0.38
TURBINE			1.9 EFF(P)=0.91
COOLER	.012	.720	155.9
COMPRESSOR			15.3 EFF(P)=0.88
HEATER	.0004		
BOILER	.078		EFF=0.94

HEATER CYCLE: PRESSURE RATIO= 4.79  
 TOTAL PRESSURE DROP=.43  
 AIR FLOW(Lbm/s)= 38.22  
 FUEL FLOW(Lbm/s)= 3.17

STATE	TEMP(deg R)		
1h	535.0		
2h	835.2		
3h	1333.3		
4h	4721.2		
5h	1404.9		
6h	945.0		
7h	760.0		
COMPONENT	DPP	DHD	VOL(cu ft)
RECUP	.267	.650	2.1 EFF=0.87
TURBINE			0.8 EFF(P)=0.39
HEATER	.066	.550	7.7
COMPRESSOR			11.4 EFF(P)=0.85

RANKINE CYCLE: SATURATION PRESSURE= 200.0  
 STEAM FLOW(Lbm/s)= 7.92  
 FLOW RATIO=0.0422

STATE	TEMP(deg R)	PRESSURE(psi)	
1s	540.0	0.5	
2s	555.0	200.0	
SF	841.8	200.0	
3s	1012.6	200.0	
4s	540.0	0.5	QUAL=0.849
COMPONENT	VOL(cu ft)		
BOILER	782.4		
TURBINE	21.0	EFF(1S)=0.88	
CONDENSER	183.6		

BRAYTON CYCLE: PRESSURE RATIO= 8.00  
 WORKING PRESSURE= 135.0  
 TOTAL PRESSURE DROP= .10  
 MASS FLOW(Lbm/s) = 131.22

STATE	TEMP(deg R)	SUMMARY: THERMAL EFF=0.460
1	540.0	HEATER EFF=0.933 (PHI=0.90)
2	1049.3	SFC(Lbm/HP-hr)=0.459
3	1272.5	VOL TOTAL(cu ft)=1550.7
4	2060.0	POWER(HP)=25000.0
5	1302.9	WORK FRAC BY STM CYCLE=0.225
6	1080.2	
PP	876.8	
7	816.3	

COMPONENT	DPP	DHD	VOL(cu ft)	
REGEN	.010	.950	13.1	EFF=0.32
TURBINE			1.6	EFF(P)=0.91
COOLER	.010	.312	181.1	
COMPRESSOR			15.1	EFF(P)=0.32
HEATER	.0004			
BOILER	.080			EFF=0.94

HEATER CYCLE: PRESSURE RATIO= 4.79  
 TOTAL PRESSURE DROP=.43  
 AIR FLOW(Lbm/s)=38.45  
 FUEL FLOW(Lbm/s)= 3.19

STATE	TEMP(deg R)	
1h	535.0	
2h	835.2	
3h	1298.2	
4h	4692.5	
5h	1372.5	
6h	945.0	
7h	760.0	

COMPONENT	DPP	DHD	VOL(cu ft)	
RECUP	.256	.650	2.1	EFF=0.26
TURBINE			0.8	EFF(P)=0.39
HEATER	.076	.598	6.5	
COMPRESSOR			11.5	EFF(P)=0.25

RANKINE CYCLE: SATURATION PRESSURE=200.0  
 STEAM FLOW(Lbm/s)= 8.97  
 FLOW RATIO=0.0495

STATE	TEMP(deg R)	PRESSURE(psi)
1s	540.0	0.5
2s	555.0	200.0
SF	841.8	200.0
3s	1045.2	200.0
4s	540.0	0.5
		QUAL=0.359

COMPONENT	VOL(cu ft)	
BOILER	1083.1	
TURBINE	25.5	EFF(IS)=0.28
CONDENSER	210.2	

BRAYTON CYCLE: PRESSURE RATIO= 9.00  
 WORKING PRESSURE=135.0  
 TOTAL PRESSURE DROP=.10  
 MASS FLOW(Lbm/s)=176.95

STATE	TEMP(deg R)	SUMMARY: THERMAL EFF=0.456		
1	540.0	HEATER EFF=0.933 (PHI=0.90)		
2	1089.0	SFC(Lbm/HP-hr)=0.484		
3	1245.0	VOL TOTAL(cu ft)=1950.3		
4	2060.0	POWER(HP)=25000.0		
5	1266.2	WORK FRAC BY STM CYCLE=0.260		
6	1110.2			
DP	376.8			
7	308.2			
COMPONENT	DPP	DHD	VOL(cu ft)	
REGEN	.010	.950	12.7	EFF=0.88
TURBINE			1.4	EFF(P)=0.91
COOLER	.010	.904	197.5	
COMPRESSOR			15.0	EFF(P)=0.88
HEATER	.0004			
BOILER	.080			EFF=0.94

HEATER CYCLE: PRESSURE RATIO= 4.79  
 TOTAL PRESSURE DROP = .43  
 AIR FLOW(Lbm/s)= 38.80  
 FUEL FLOW(Lbm/s)= 3.22

STATE	TEMP(deg R)			
1h	535.0			
2h	835.2			
3h	1268.3			
4h	4668.2			
5h	1345.0			
6h	945.0			
7h	760.0			
COMPONENT	DPP	DHD	VOL(cu ft)	
RECUP	.245	.650	2.2	EFF=0.85
TURBINE			0.8	EFF(P)=0.89
HEATER	.087	.646	5.7	
COMPRESSOR			11.7	EFF(P)=0.85

RANKINE CYCLE: SATURATION PRESSURE= 200.00  
 STEAM FLOW(Lbm/s)= 9.90  
 FLOW RATIO=0.0560

STATE	TEMP(deg R)	PRESSURE(psi)	
1s	540.0	0.5	
2s	555.0	200.0	
SF	841.8	200.0	
3s	1075.2	200.0	
4s	540.0	0.5	QUAL=0.867
COMPONENT	VOL(cu ft)		
BOILER	1439.0		
TURBINE	29.8	EFF(IS) =0.88	
CONDENSER	234.5		

BRAYTON CYCLE: PRESSURE RATIO=10.00  
 WORKING PRESSURE=135.0  
 TOTAL PRESSURE DROP=.10  
 MASS FLOW (Lbm/s)=174.00

STATE	TEMP(deg R)	SUMMARY: THERMAL EFF=0.451		
1	540.0	HEATER EFF=0.933 (PHI=0.90)		
2	1125.1	SFC(Lbm/HP-hr)=0.469		
3	1221.1	VOL TOTAL(cu ft)=2403.0		
4	2060.0	POWER(HP)=25000.0		
5	1234.2	WORK FRAC BY STM CYCLE=0.296		
6	1138.1			
PP	876.7			
7	800.9			
COMPONENT	DPP	DHD	VOL(cu ft)	
REGEN	.010	.950	12.4	EFF=0.88
TURBINE			1.3	EFF(P)=0.91
COOLER	.008	.996	232.3	
COMPRESSOR			14.9	EFF(P)=0.88
HEATER	.0004			
BOILER	.082			EFF=0.94

HEATER CYCLE: PRESSURE RATIO= 4.79  
 TOTAL PRESSURE DROP=.43  
 AIR FLOW(Lbm/s)= 39.22  
 FUEL FLOW(Lbm/s)= 3.25

STATE	TEMP(deg R)			
1h	535.0			
2h	835.2			
3h	1242.5			
4h	4647.3			
5h	1321.1			
6h	945.0			
7h	760.0			
COMPONENT	DPP	DHD	VOL(cu ft)	
RECUP	.235	.650	2.2	EFF=0.84
TURBINE			0.8	EFF(P)=0.89
HEATER	.098	.694	5.0	
COMPRESSOR			11.9	EFF(P)=0.85

RANKINE CYCLE: SATURATION PRESSURE= 199.9  
 STEAM FLOW(Lbm/s)= 10.76  
 FLOW RATIO=0.0618

STATE	TEMP(deg R)	PRESSURE(psi)	
1s	540.0	0.5	
2s	555.0	199.9	
SP	841.7	199.9	
3s	1103.1	199.9	
4s	540.0	0.5	QUAL=0.875
COMPONENT	VOL(cu ft)		
BOILER	1830.6		
TURBINE	34.0	EFF(1S)=0.88	
CONDENSER	257.1		

**MED**  
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