Thermo Electron
CORPORATION

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HIGH-TEMPERATURE ORGANIC RANKINE BOTTOMING CYCLE FOR HEAVY-DUTY TRANSPORT

Presentation Material for
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Prepared for

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SUMMARY

A parametric computer analysis has been conducted for a Rankine bottoming cycle utilizing the organic working fluid RC-1, which is a mixture of 60 mole percent pentafluorobenzene (PFB) and 40 mole percent hexafluorobenzene (HFB). The RC-1 is a higher temperature organic working fluid that is capable of operation with the increased waste heat temperature levels of the adiabatic engine.

Initial efforts consisted of acquisition of the RC-1 thermodynamic properties from Monsanto with subsequent storage and formating of the tables for use in Thermo Electron's computer programs.

Studies were made of the effect on performance by varying system component sizes and other variables. The curves and tables in this handout show a sample of the many iterations and computations undertaken to optimize the system.

Data on an adibatic engine in four different configurations were supplied by NASA/Lewis, and the performance of a Rankine bottoming cycle system has been computed for this engine with varying exhaust gas temperature conditions. The following tables show the results of this analysis in the format requested. Bottoming cycle power output reaches 53 horsepower, which represents a 16.6-percent increase in the 317 horsepower turbocharged (TC) diesel engine to yield a compound engine power output of 370 horsepower. The brake specific fuel consumption (BSFC) for the turbocompound engine with a bottoming cycle system is 0.260 lb/bhp-hr. The temperature sensitivity table shows that the compound engine BSFC is 0.254 lb/bhp-hr and this represents an 18.1-percent reduction in fuel consumption and a bottoming cycle system power output of 71 horsepower for the "elastic" adiabatic engine with an exhaust temperature of 1600°F.

TABLE I

RC_1 PARAMETRIC ANALYSIS

BASELINE CASE:

ΔP_{VG} = 70 PSID

$\Delta P_{COND.}$ = 0.5 PSID

$\Delta P_{REGN.\ LIQ.}$ = 10 PSID

$\Delta P_{REGN.\ VAP.}$ = 0.5 PSID

ΔT_{VG} (MIN.) = 35°F

REGENERATOR EFF. = 90%

PUMP EFF. = 50%

$T_{COND.}$ = 170°F

TURBINE THERMAL EFF. = 0.75

TURBINE MECH. EFF. = 0.95

$T_{EXH.\ GAS\ RANGE}$: $1000°F \leq T \leq 1400°F$

$T_{TURBINE\ INLET\ RANGE}$: $600°F \leq T \leq 900°F$

$P_{TURBINE\ INLET\ RANGE}$: $300\ PSIA \leq P \leq 1000\ PSIA$

$P_{CRITICAL}$ = 411 PSIA

$T_{CRITICAL}$ = 456°F

EXHAUST GAS FLOW RATE = 4000 LB/HR

$$\left(Cp_{\ GAS} = 0.26\ \frac{BTU}{LBM\text{-}°F)}\right)$$

$T_{EXHAUST\ MIN.\ STACK\ TEMP.}$ = 300°F

$$\text{CONVERSION EFF.} = \frac{BHP}{\dot{m} \times Cp \times (T_{EXH.\ IN} - 300°F)}$$

TABLE II
PARAMETRIC STUDY VARIATIONS

CASE I BASELINE CASE

WITH $P_{TURBINE\ INLET}$ = 300, 400, 500, 700, 1000 PSIA

AND $T_{EXH.\ GAS}$ = 1000°, 1200°, 1400°F

CASE II VARIATION OF CONDENSING TEMPERATURE

$T_{COND.}$ = 140°, 160°F

CASE III VARIATION OF REGENERATION TEMPERATURE

$N_{REGN.}$ = 0, 0.5, 0.75

CASE IV VARIATION OF TURBINE EFFICIENCY

$N_{TN.}$ = 0.65, 0.75

CASE V VARIATION IN MINIMUM APPROACH TEMPERATURE IN VAPOR GENERATOR

$\Delta T_{MIN.}$ = 70°, 100°F

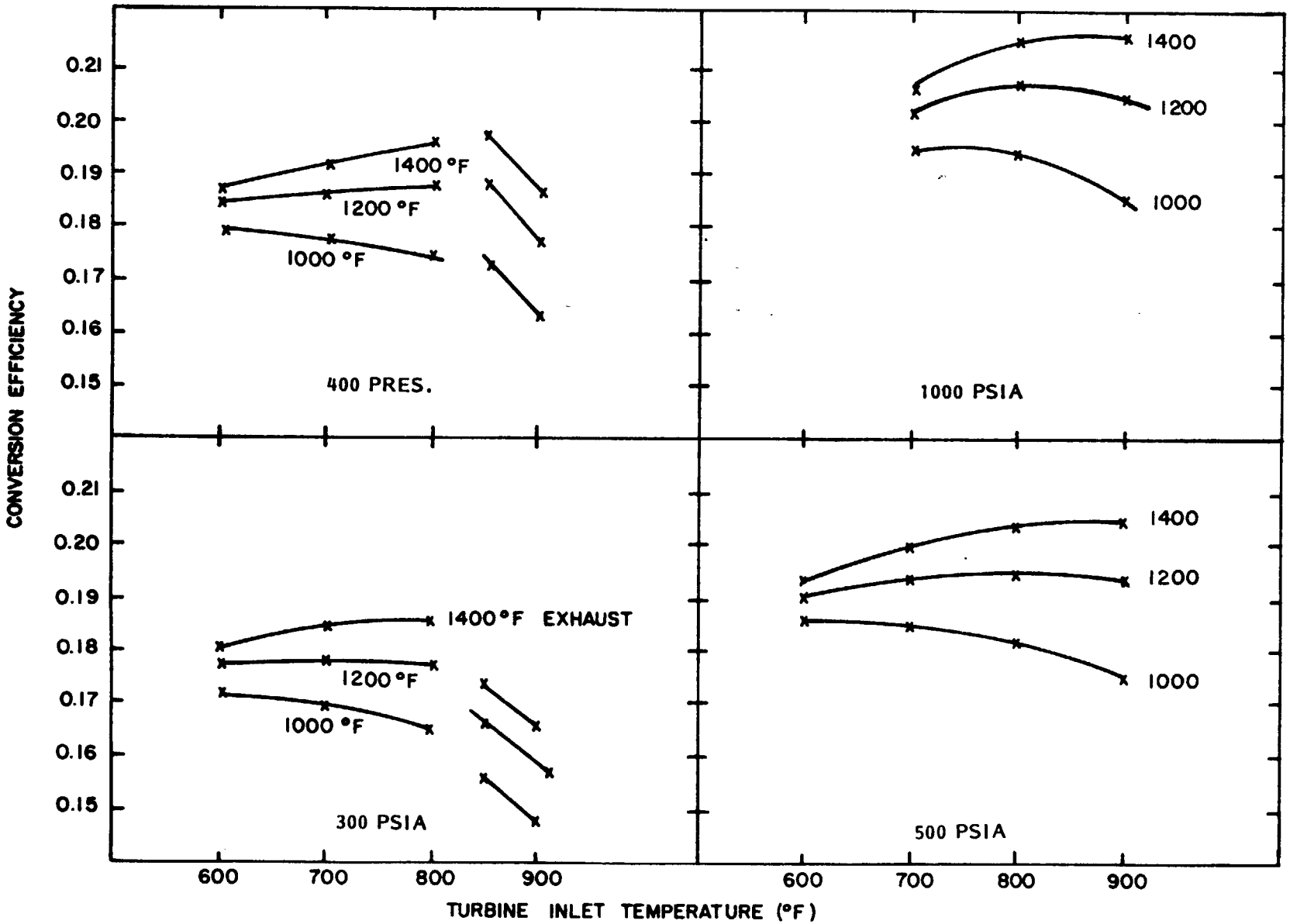
EFFECT OF COMPONENT PRESSURE DROP ON CONVERSION EFFICIENCY

Exhaust Temperature	1000°F								1200°F								1400°F							
Turbine Pressure	300		400		500		1000		300		400		500		1000		300		400		500		1000	
Turbine Temperature	700	900	700	900	700	900	700	900	700	900	700	900	700	900	700	900	700	900	700	900	700	900	700	900
$\frac{\eta_{conv.}}{\eta_{conv.\ ideal}}$	0.97	0.99	0.97	0.98	0.97	0.96	0.97	0.97	0.97	0.99	0.96	0.98	0.97	x	0.97	0.97	0.96	0.99	0.97	0.99	0.97	x	0.96	0.97

$\eta_{conv.}$ = Conversion Efficiency with Component Pressure Drops Shown for Case I

$\eta_{conv.\ ideal}$ = Conversion Efficiency with Component Pressure Drops Equal to Zero (0)

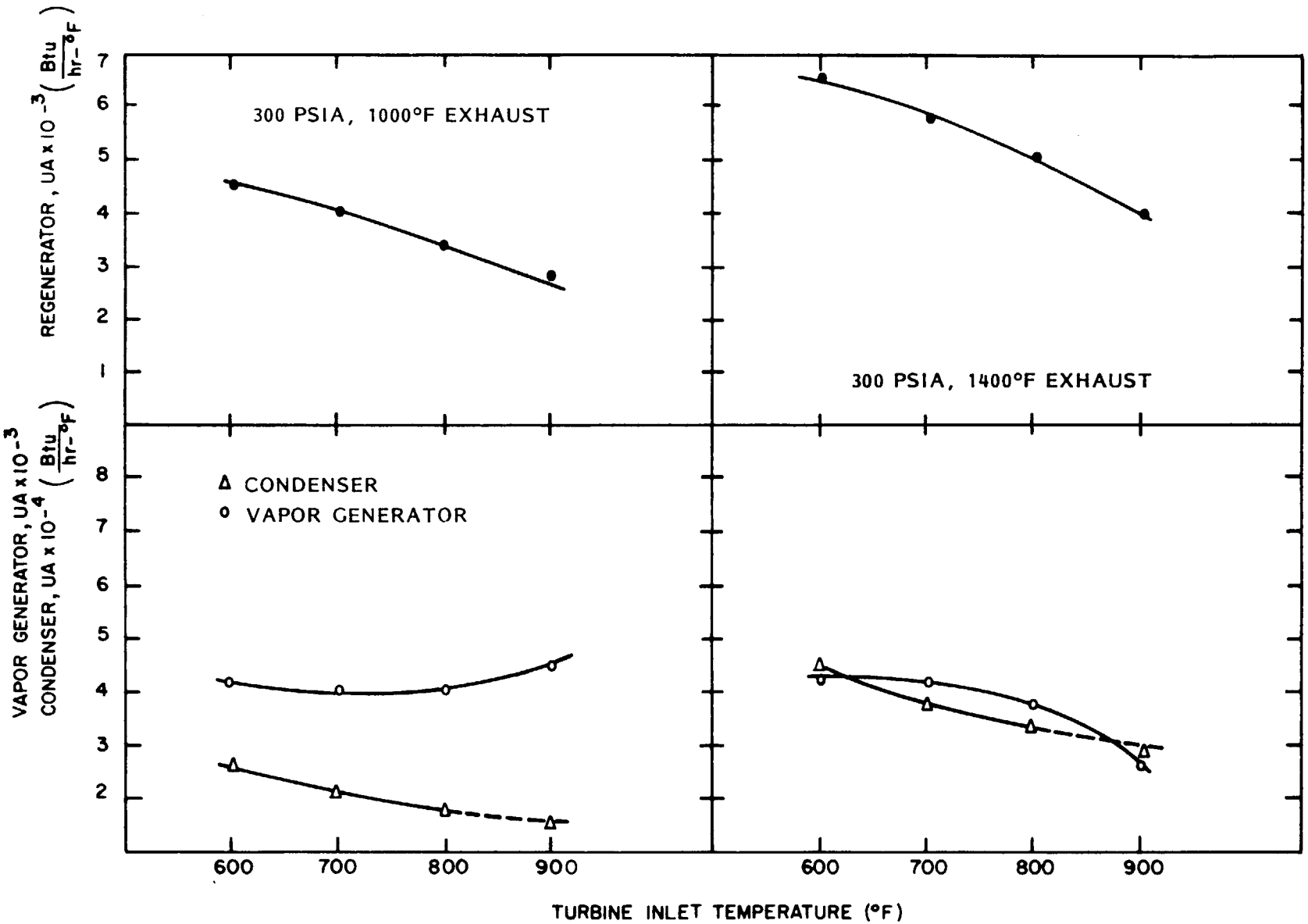
CASE I



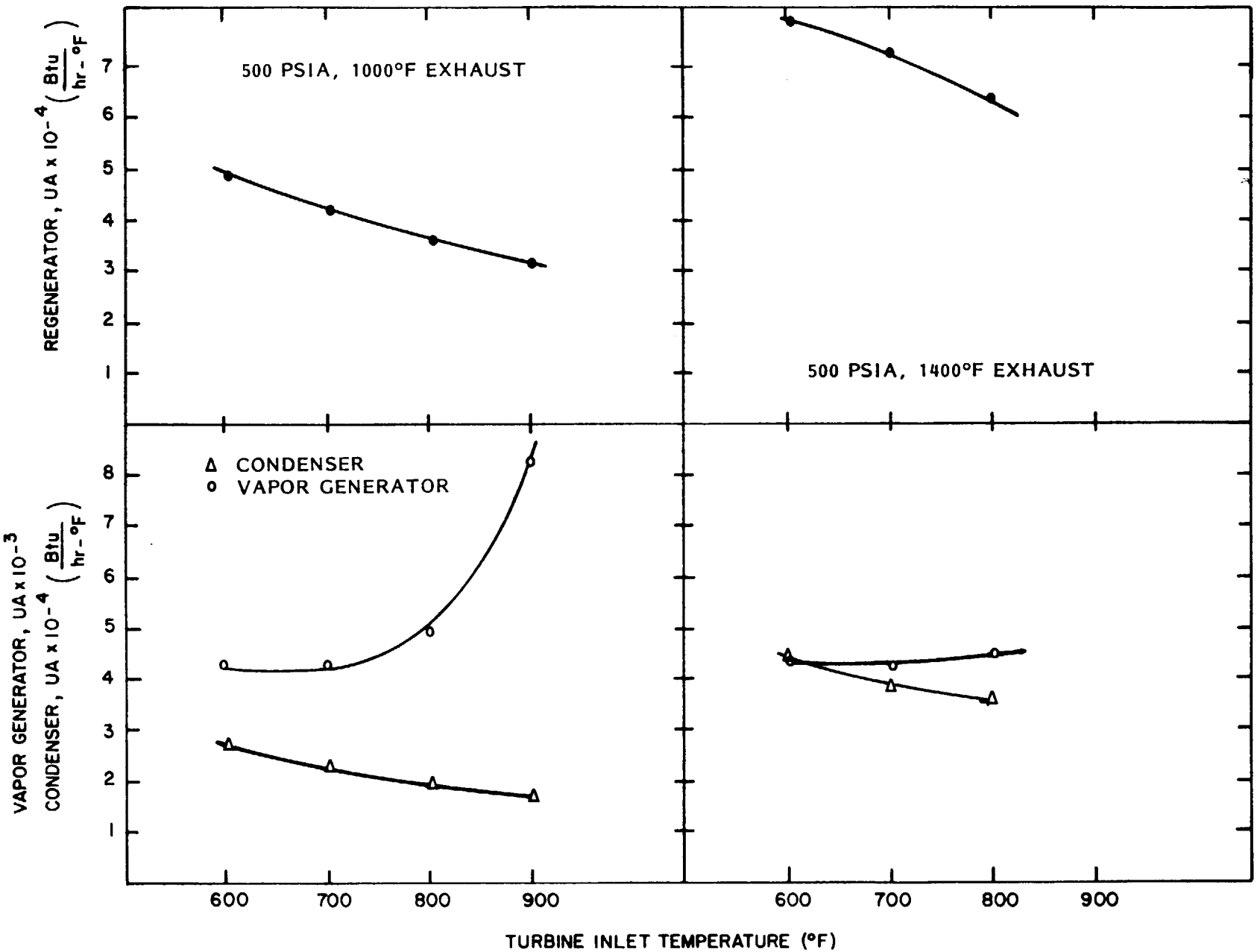
$\Delta T_{MIN} = 35$ $\eta_{REGEN} = 0.9$ $\Delta P \neq 0$ FOR COMPONENTS

$T_{COND} = 170°F$ $\eta_{TUR} = 0.75$ $\eta_{MECH} = 0.95$

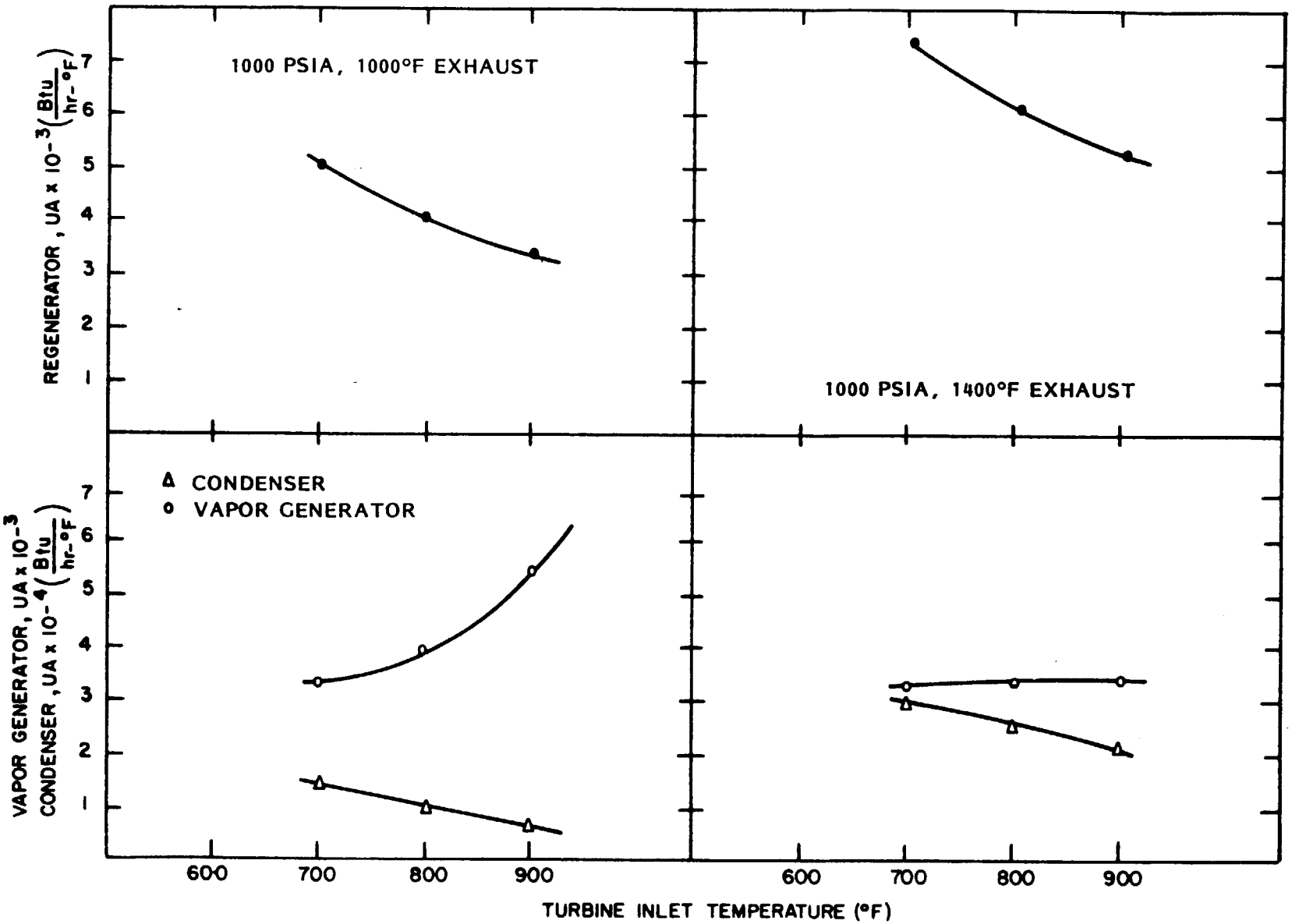
CASE I


REGENERATOR, UA x 10^-3 (Btu/hr-°F)
VAPOR GENERATOR, UA x 10^-3
CONDENSER, UA x 10^-4 (Btu/hr-°F)
300 PSIA, 1000°F EXHAUST
300 PSIA, 1400°F EXHAUST
Δ CONDENSER
o VAPOR GENERATOR
TURBINE INLET TEMPERATURE (°F)
600
700
800
900

CASE I


500 PSIA, 1000°F EXHAUST
500 PSIA, 1400°F EXHAUST
REGENERATOR, UA x 10^-4 (Btu/hr-°F)
VAPOR GENERATOR, UA x 10^-3
CONDENSER, UA x 10^-4 (Btu/hr-°F)
Δ CONDENSER
o VAPOR GENERATOR
TURBINE INLET TEMPERATURE (°F)
600
700
800
900

CASE I


1000 PSIA, 1000°F EXHAUST
1000 PSIA, 1400°F EXHAUST
REGENERATOR, UA x 10^-3 (Btu/hr-°F)
VAPOR GENERATOR, UA x 10^-3
CONDENSER, UA x 10^-4 (Btu/hr-°F)
Δ CONDENSER
o VAPOR GENERATOR
1
2
3
4
5
6
7
600
700
800
900
TURBINE INLET TEMPERATURE (°F)

CASE I
BASELINE PERFORMANCE

Exhaust Temperature In	1000°F								1200°F								1400°F							
Turbine Pressure	300		400		500		1000		300		400		500		1000		300		400		500		1000	
Turbine Temperature	700	900	700	900	700	900	700	900	700	900	700	900	700	900	700	900	700	900	700	900	700	900	700	900
$\frac{(\eta_{conv.})}{(\eta_{conv.})_o}$	1	0.87	1.047	0.967	1.095	1.041	1.151	1.098	1.05	0.938	1.101	1.047	1.148	1.145	1.192	1.207	1.089	0.979	1.136	1.101	1.183	1.213	1.219	1.278
$UA_{regen.}$	1	0.708			1.011	0.775	1.275	0.850	1.364				1.421	1.108	1.683	1.22	1.45	1.225			1.80	1.300	1.838	1.325
$(UA/HP)_{regen.}$	83.1	66.9			79.7	62.2	90.6	65.0	83.0	66.9			79.6	62.3	90.6	65.0	83.1	66.9			79.7	62.3	90.6	65.1
$UA_{cond.}$	1	0.738			1.048	0.810	1.143	0.810	1.464	1.054			1.474	1.166	1.541	1.155	1.76	1.333			1.81	1.667	1.905	1.476
$(UA/HP)_{cond.}$	468.0	379.8			433.8	343.7	435.5	322.4	467.9	379.5			433.5	343.9	435.5	322.5	468.4	379.8			433.8	343.9	435.5	322.6
UA_{vg}	1	1.125			1.063	2.08	1.10	1.6	1.013	0.765			1.054	1.483	1.072	1.183	1.038	0.65			1.075	1.188	1.075	1.100
$(UA/HP)_{vg}$	83.0	107.9			80.8	165.1	78.3	120.5	61.7	52.5			59.1	83.3	57.7	62.9	49.9	35.6			47.4		46.5	45.0

CASE II

EFFECT OF CONDENSER TEMPERATURE ON TOTAL PERFORMANCE

Exhaust Gas Temperature	1000°F								1200°F								1400°F							
Turbine Pressure	300		400		500		1000		300		400		500		1000		300		400		500		1000	
Turbine Temperature	700	900	700	900	700	900	700	900	700	900	700	900	700	900	700	900	700	900	700	900	700	900	700	900
$UA_{cond.}$ (T_c = 170°F)	1	0.738			1.048	0.81	1.143	0.810	1.46	1.054			1.474	1.166	1.541	1.155	1.76	1.333			1.81	1.667	1.905	1.476
(UA/HP)	468	380			434	344	436	322									468	380			434	344	436	323
$UA_{cond.}$ (T_c = 160°F)	1.72	1.19			1.75	1.28	1.86	1.28									2.9	2.1			2.96	2.34	3.1	2.34
(UA/HP)	724	573			674	523	683	494									723	573			675	522	683	494
$\eta_{conv.}/\eta_{conv.,o}$	1.03	0.90			1.12	1.07	1.18	1.13									1.12	1.02			1.21	1.24	1.25	1.31
$UA_{cond.}$ (T_c = 140°F)	1.37	0.997			1.39	1.05	1.47	1.09									2.32	1.76			2.33	1.9	2.43	1.93
(UA/HP)	529	432			497	396	501	375									530	431			497	396	501	375
$\eta_{conv.}/\eta_{conv.,o}$	1.12	1			1.22	1.15	1.28	1.26									1.21	1.13			1.3	1.34	1.34	1.42

CASE III

EFFECT OF REGENERATOR EFFICIENCY ON TOTAL PERFORMANCE

Exhaust Gas Temperature	1000°F						1400°F					
Turbine Pressure	300		500		1000		300		500		1000	
Turbine Temperature	700	900	700	900	700	900	700	900	700	900	700	900
at Regn. Eff. = 0.90												
$\eta_{conv.}/\eta_{conv.,o}$	1	0.87	1.1	1.04	1.15	1.1	1.1	0.98	1.18	1.21	1.22	1.28
$UA_{regn.}/UA_{regn.,o}$	1	0.71	1.01	0.78	1.28	0.85	1.45	1.23	1.80	1.30	1.84	1.33
(UA/HP)	83	67	80	62	91	65	83	67	80	62	91	65
at Regn. Eff. = 0.75												
$\eta_{conv.}/\eta_{conv.,o}$	0.953		1.05	0.98	1.11	1.07	1.02		1.11	1.11	1.16	1.20
$UA_{regn.}/UA_{regn.,o}$	0.50		0.51	0.39	0.58	0.41	0.83		0.85	0.69	0.94	0.72
(UA/HP)	43.2		40.6	32.8	42.9	31.9	43.3		40.5	32.9	42.8	31.9
at Regn. Eff. = 0.50												
$\eta_{conv.}/\eta_{conv.,o}$	0.91	0.817	0.99	0.91	1.07	1.01	0.93	0.88	1.02	0.98	1.08	1.07
$UA_{regn.}/UA_{regn.,o}$	0.20	0.16	0.21	0.16	0.23	0.17	0.33	0.27	0.33	0.27	0.36	0.28
(UA/HP)	18.5	16.1	17.2	14.6	17.6	13.8	18.5	16.2	17.1	14.6	17.6	13.8
UA/UA_o Vapor. Gen.												
at $\eta_{regn.}$ = 0.90	1	1.125	1.06	2.1	1.1	1.6	1.04	0.65	1.08	1.19	1.08	1.10
at $\eta_{regn.}$ = 0.75	1.10	1.36	1.14	1.85	1.15	1.75	1.19	1.24	1.1	1.24	1.12	1.22
at $\eta_{regn.}$ = 0.50	1.27	1.63	1.27	1.83	1.26	1.81	1.19	1.24	1.19	1.29	1.18	1.29

CASE V

EFFECT OF VAPOR GENERATOR PINCH POINT TEMPERATURE ON TOTAL PERFORMANCE

Exhaust Temperature	1000°F						1400°F					
Turbine Pressure	300		500		1000		300		500		1000	
Turbine Temperature	700	900	700	900	700	900	700	900	700	900	700	900
$\Delta T_{vg} = 35$												
$UA/UA_{vg,o}$	1	1.125	1.06	2.08	1.1	1.6	1.04	0.65	1.08	1.19	1.08	1.1
$\eta_{conv.}/\eta_{conv.,o}$	1	0.87	1.10	1.04	1.15	1.1	1.09	0.98	1.18	1.21	1.22	1.28
UA/HP	83	108	81	165	78	121	50	36	47		47	45
$\Delta T_{vg} = 70$												
$UA/UA_{vg,o}$	0.75	0.93	0.80	1.40	0.82	1.19	0.81	0.60	0.84	1.02	0.85	0.90
$\eta_{conv.}/\eta_{conv.,o}$	0.94	0.817	1.03	0.96	1.08	1.02	1.05	0.94	1.14	1.166	1.18	1.23
UA/HP	66	94.6	64.6	119.9	62.7	96.8	40.7	33.3	38.9	46.1	38.2	38.5
$\Delta T_{vg} = 100$												
$UA/UA_{vg,o}$	0.62	0.79	0.67	1.09	0.68	0.97	0.70	0.55	0.73	0.86	0.74	0.78
$\eta_{conv.}/\eta_{conv.,o}$	0.89	0.76	0.97	0.90	1.03	0.95	1.02	0.91	1.10	1.12	1.14	1.18
UA/HP	58.0	86.3	56.9	100.4	55.2	84.2	36.3	31.6	34.7	40.4	34.1	34.7

		T	P	H		DT	DP	DH
14	BOIL IN	327.65	870.00	82.25	BOIL	422.352	70.000	150.423
1	OUT	750.00	800.00	232.67	LINE	.000	.000	.000
2	ENG IN	750.00	800.00	232.67	ENG	198.423	789.910	36.815
3	OUT	551.58	10.09	195.86	LINE	.000	.000	.000
4	REGV IN	551.58	10.09	195.86	REGV	220.419	.500	49.996
5	OUT	331.16	9.59	145.86	LINE	.000	.000	.000
6	COND IN	331.16	9.59	145.86	COND	182.910	.500	117.314
9	OUT	148.25	9.09	28.55	LINE	.000	.000	.000
10	PUMP IN	148.25	9.09	28.55	PUMP	13.547	-870.910	3.705
11	OUT	161.80	880.00	32.25	LINE	.000	.000	.000
12	REGL IN	161.80	880.00	32.25	REGL	165.853	10.000	49.996
13	OUT	327.65	870.00	82.25	LINE	.000	.000	.000

SYSTEM

FLOWRATE = 4401. HP = 52.55 EFF = 20.20

EXPANDER Q = .1620E 06 HP = 58.96

EFFTH = .7650 EFFME = .9260 EFFALL = .7084

WES = 48.12 WSHAFT = 34.09 WNET = 30.39

EXHAUST QUALITY = 1.000

REGENERATOR EFF = .6000 Q = .2201E 06

UA = 1126.

CONDENSER Q = .5164E 06 UATOTAL = 42771.

HSUB = 1.41 HDESUP = 33.84 HLATENT = 82.06

UASUB = 592. UACOND = 39298. UADESUP = 2881.

TWATER IN = 140.0 TWATER OUT = 150.0 WATERFLOW = 51635.

BOILER Q = .6621E 06 UATOTAL = 3635.

HSENS = 59.75 HLATENT = .00 HSUPER = 90.67

TBSUP = 178.91

UASENS = 2520. UALAT = 0. UASUPER = 1115.

PUMP

EFF = .5000 GPM = 6.47 HP = 6.41

GAS

FLOWRATE = 2886 TGASI = 1240.0 TGASO = 357.6

TPINCH = 708.1 DTPINCH = 30.0

```
!START $
?800.,750.,4408.,10.09,10.,10000.,3000.,1
 STEAM CALC.S TRUE OR FALSE
?.FALSE.
 P1 = 800.000
T1 = 750.000
FLOW = 4408.00
PE = 10.0900
VERSP = 10.0000
 RLIFE = 10000.0
ARPM = 3000.00
INPUT NTNF (FIRST STAGE TO BE RUN)
?1
 INPUT NTNL (LAST STAGE TO BE RUN)
?1
 INPUT NOPT=1 FOR OPT. RUNS...NOPT=0 IF NO
?0
  1STAGES                                STAGE NUMBERS
          1          2          3          4          5          6          7
 PIN
   800.00
TIN
   749.37
 PEST
     9.84
HSTAGE
    48.42
 STNS
    56.26
 SD
     1.46
 D
     3.47
 BHEIGHT
      .23
 VRM
      .50
 TIPVEL
   835.67
 REACTION
      .00
 UU
   779.83
ALPHA2
    16.00
BETA2
    31.54
W2
   802.21
 RELMC2
     1.76
ALPHA3
    90.00
BETA3
    15.20
W3
   808.09
RELMC3
     1.77
PTHH
   498.23
VTHH
      .12
HWORK
    36.82
 TTE
      .86
STE
      .76
```

```
OVERALL    PERFORMANCE
 GBR(1-7)
      .18372E 02
GBN
      .30000E 01
SHAFT
      .44017E 00
THRUST
      .12031E 01
 ROTWT
      .25120E 00
 BRGNO
      .20200E 03
BRGSHAFT
      .59055E 00
BLIFE
      .17213E 06
 AVGLIFE
      .86067E 06
SEALD
      .89055E 00
SEALSP
      .21417E 03
SEALHP
      .72790E 00
THEFF
      .76503E 00
 HPTHERM
      .63717E 02
GBEF
      .94929E 00
MECHEF
      .97572E 00
TGUEF
      .70861E 00
TRPMM
      .55117E 05
TGUHPNET
      .59017E 02
**STOP** 0
```

DIESEL ENGINE DATA

DIESEL CONFIGURATION	BHP	BSFC (LB/BHP-HR)	EXHAUST (°F)	EXHAUST (LB/MIN)
TC	317	0.315	1240	48.1
TC/A	320	0.310	1120	47.6
TCPD	335	0.297	1140	47.8
TCPD/A	340	0.293	1060	48.4

BOTTOMING CYCLE DATA

DIESEL CONFIGURATION	EXPANDER η (1) (%)	CYCLE η (2) (%)	BHP	EXHAUST (3) (°F)	CONVERSION η (4) (%)	TGU (5) OVERALL EFF.	Q/Q_o (6)
TC	76.5	20.2	52.6	358	19	70.8	1.063
TC/A	78.8	21.1	47.5	349	19.8	72.8	0.919
TCPD	76.5	20.1	46.1	358	18.7	70.6	0.936
TCPD/A	76.5	19.7	42.5	334	18.8	70.8	0.879

(1) $\eta_{EXPANDER} = \frac{\text{TURBINE THERMAL POWER OUTPUT}}{\text{ISENTROPIC IDEAL POWER}} \frac{(\Delta H)}{(\Delta H_s)}$

(2) $\eta_{CYCLE} = \frac{BHP}{\dot{m} \times Cp \times (\Delta T)_{ACTUAL}}$; Cp = 0.26 BTU/LBM-°F

(3) EXHAUST GAS STACK TEMPERATURE (OUT OF VAPOR GENERATOR)

(4) $\eta_{CONVERSION} = \frac{BHP}{\dot{m} \times Cp \times (T_{GAS\ IN} - 300)}$

(5) TGU = TURBINE GEARBOX UNIT OVERALL EFFICIENCY

(6) $Q/Q_o = \frac{[\dot{m} \times Cp \times (T_{GAS\ IN} - T_{GAS\ OUT})]\ \text{THIS STUDY}}{[\dot{m} \times Cp \times (T_{GAS\ IN} - T_{GAS\ OUT})]\ \text{EXISTING MACK-ORCS}}$

COMPOUND ENGINE SYSTEM DATA

DIESEL CONFIG.	BHP	BSFC (LB/BHP-HR)	$\Delta BSFC^{(1)}$ (%)	$\Delta HP^{(2)}$ (%)	$\Delta HP_{FL85}^{(3)}$ (%)
TC	369.6	0.270	14.2	16.6	14.8
TC/A	367.5	0.270	12.9	14.8	13.0
TCPD	381.1	0.261	12.1	13.8	12.8
TCPD/A	382.5	0.260	11.1	12.5	11.6

(1) $$\Delta BSFC\ (\%) = \left(1 - \frac{(BSFC)_{COMPOUND}}{(BSFC)_{WITHOUT\ COMPOUND}}\right) \times 100$$

(2) $$\Delta HP\ (\%) = \left(\frac{HP_{COMPOUND}}{HP_{WITHOUT\ COMPOUND}} - 1\right) \times 100$$

(3) $$\Delta HP_{FL85}\ (\%) = \left(\frac{HP_{FL85\ ORCS}}{HP_{WITHOUT\ COMPOUND}} - 1\right) \times 100$$

HEAT EXCHANGER DATA
(Based on 1120°F/47.6 lb/min Diesel Exhaust)

NAME	TYPE	FLUIDS	Q (BTU/HR)	A $(FT)^2$	$\frac{UA}{(UA_o)}$ (1)	SIZE INCREASE (IN.)
VAPOR GENERATOR	FINNED TUBE, COUNTERFLOW	EXHAUST RC1	572,300	463	1.11	4 LENGTH
CONDENSER	PLATE FIN, CROSSFLOW	WATER RC1	440,000 (T_{COND} = 155°F)	341	1.44	6.5 LENGTH
REGENERATOR	CONTINUOUS FINNED TUBE, CROSSFLOW	$RC1_{VAPOR}$ $RC1_{LIQ.}$	177,400	82	1.98	1.5 DEPTH

(1) $\frac{UA}{UA_o} \equiv \frac{\text{HEAT EXCHANGER, UA (BTU/HR-°F)}}{\text{MACK-ORCS HEAT EXCHANGER UA (BTU/HR-°F)}}$

102-383

TEMPERATURE SENSITIVITY
(Based on TC/A Diesel Configuration)

DIESEL (°F)	BOTTOMER (BHP)	COMPOUND (BSFC)	ΔBSFC (%)
1000	38.9	0.276	11.0
1200	50.8	0.268	13.5
1400	60.7	0.261	15.8
1600	70.7	0.254	18.1

TEMPERATURE SENSITIVITY
(Based on TC/A Diesel Configuration) For High Performance Cycle (HPC)

DIESEL (°F)	BOTTOMER (BHP)	COMPOUND (BSFC)	BSFC (%)	COMPOUND (BHP)
1000	57.4	0.263	15.2	377
1200	74.0	0.252	18.7	394
1400	90.8	0.241	22.3	411
1600	107.5	0.232	25.2	428

ANALYSIS CONDITIONS

η_{TGU} = 0.77

$\eta_{REGEN.}$ = 0.90

$T_{COND.}$ = 167°F

ΔP COMPONENTS AND LINES = 0 PSID

ΔT_{VG} (MIN.) = 35°F

$T_{EXHAUST}$ MIN. STACK TEMP. = 300°F

Cp_{GAS} = 0.26 BTU/LBM-°F

$P_{TURBINE\ INLET}$ = 1000 PSIA

$T_{TURBINE\ INLET}$ = 900°F