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A Sensitivity Study of Brayton Cycle Power Plant Performance

C. C. Hiller

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A SENSITIVITY STUDY OF BRAYTON CYCLE POWER PLANT PERFORMANCE

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ABSTRACT

This study investigates the efficiency of Brayton cycle power plants under a variety of design configurations. The study is unique in that the range of cycle parameters and configurations examined is beyond that generally discussed in the open literature. The parameters and configurations include:

1. Open and closed air cycles
2. Optimum pressure ratio
3. Helium versus air working fluids
4. Turbine and compressor isentropic efficiencies
5. Recuperator effectiveness
6. Turbine inlet temperature
7. Heat rejection temperature
8. Pressure drop losses
9. With/without intercooling
10. With/without reheat

Equation derivations, a computer listing, and a hand calculator program listing are included in the appendices so that variations other than those presented in the report may be studied.

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NOMENCLATURE

η_{CYCLE}	overall cycle efficiency
η_c	compressor isentropic efficiency
η_t	turbine isentropic efficiency
PR	pressure ratio across turbine
PDR	pressure drop ratio $PDR \equiv \frac{\text{pressure ratio across compressor}}{\text{pressure ratio across turbine}}$ $PDR \geq 1$
ϵ	recuperator effectiveness $0 \leq \epsilon \leq 1$
$\dot{m}$	mass flow rate
$\dot{W}_t$	turbine work output rate
$\dot{W}_c$	compressor work input rate
$\dot{Q}_{IN}$	heat input rate
$\dot{Q}_{OUT}$	heat rejection rate
T	absolute temperature
P	absolute pressure
γ	ratio of specific heats $\gamma = \frac{C_p}{C_v}$ $\gamma = 1.4$ for air $\gamma = 1.67$ for helium

C_p constant pressure specific heat

C_v constant volume specific heat

$C_v = C_p - R$

R gas constant

MODE indicator of system

Mode 1 - with one stage of intercooling and one stage of reheat

Mode 2 - with one stage of reheat and no intercooling

Mode 3 - with one stage of intercooling and no reheat

Mode 4 - with no intercooling and no reheat

<u>Subscripts</u>

1 - 10 state points as indicated on Figure 1

is isentropic process

A SENSITIVITY STUDY OF BRAYTON CYCLE POWER PLANT PERFORMANCE

Introduction

Studies of Brayton cycle power plant performance available in the open literature are typically somewhat limited in scope.[1,2,3] The present brief study has been performed to show more general performance trends over a wider variety of conditions, and to provide a simple model which the reader may use to study still more parameter variations. This report assumes that the reader is familiar with Brayton cycle concepts and terminology, a review of which is available in Reference 4.

Modeling

A schematic of the family of Brayton cycle plants being examined is shown in Figure 1. Configurations without reheat, intercooling, or regeneration are included in the study. The models used are based on ideal gas behavior and are fully developed in Appendix A. A computer listing of the model is given in Appendix B, while a hand calculator program suitable for use on a reverse-polish-notation magnetic-card-reading type calculator is given in Appendix C. The model in the present study is limited in that it predicts only design point efficiency, and not off-design performance. The prediction of off-design performance is much more difficult than the present task, and a description of a model which has been developed by the author for that purpose will be the subject of an upcoming report. The models in the present study are useful for approximate off-design performance prediction if appropriate values of off-design turbine and compressor efficiencies, pressure drops, pressure ratios, and other parameters are known.

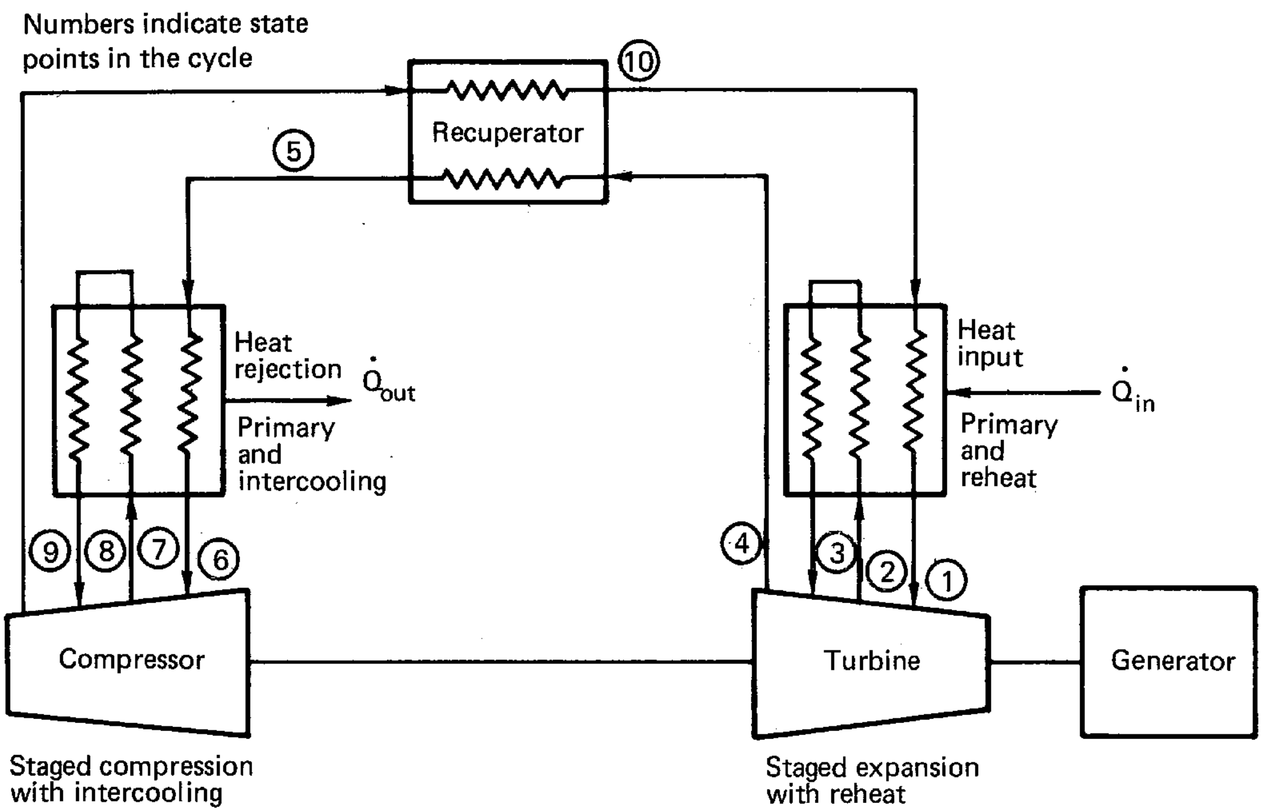

Figure 1. Brayton Cycle Power Plant

Description of Results

The scope of this study includes investigation of the following parameters:

1. Open and closed air cycles
2. Optimum pressure ratio
3. Helium versus air working fluids
4. Turbine and compressor isentropic efficiencies
5. Recuperator effectiveness
6. Turbine inlet temperature
7. Heat rejection temperature
8. Pressure drop losses
9. Intercooling
10. Reheat
11. Other factors

Open Versus Closed Air Cycles

When air is used as the working fluid it is possible to eliminate the precooler from the system, forming an open rather than a closed cycle, and forcing the low-side pressure to be atmospheric. However, from a modeling standpoint, efficiency is a function of pressure ratio and pressure drops rather than of absolute pressures. The present model is hence valid for either open or closed cycles, and open and closed air cycles will have the same efficiency if the same temperatures, recuperator effectiveness, pressure ratios, and other parameters are assumed. In practice, open cycles usually have lower efficiency than closed cycles because it is not practical to provide a recuperator of equal effectiveness in both cycles. For a given effectiveness, the closed cycle recuperator will be smaller and less expensive than an open cycle recuperator because the higher pressure of the closed cycle leads to lower pressure drop and more efficient heat transfer. Practical levels of effectiveness are currently 0.8 to 0.9 for closed cycles and 0 to 0.7 for open cycles. Rising energy costs are steadily driving practical effectiveness levels higher.

Optimum Pressure Ratio

Given any set of parameters and cycle configuration, the efficiency of a Brayton cycle will be maximum at an optimum pressure ratio and less at higher and lower pressure ratios, as shown in Figure 2. The optimum pressure ratio varies with the type of working fluid and other parameters as shown in Figures 3 through 10. All remaining efficiency values given in this report are determined at the optimum pressure ratio unless otherwise stated.

Helium Versus Air

Because ideal gas assumptions are used in the model, the only parameter distinguishing helium from air is γ, the ratio of specific heats. γ is 1.67 for helium and 1.4 for air. No significant differences in peak efficiency are apparent between helium and air for given sets of parameters, although the optimum pressure ratio to achieve maximum efficiency is typically higher for air than for helium. Figure 4 shows the efficiency of an air cycle, while Figure 5 is for helium. In practice, helium has better heat transfer characteristics than air, and therefore slightly higher levels of recuperation effectiveness are practical in helium cycles compared to closed air cycles.

Turbine and Compressor Isentropic Efficiencies

Cycle efficiency will be improved whenever the isentropic efficiency of either the compressor or turbine is improved. Figure 3 shows the sensitivity of cycle efficiency to changes in compressor and turbine efficiency for an air cycle under a given set of parameters. Other conditions may be examined by using the models provided in the appendices.

Recuperator Effectiveness

The efficiency of a Brayton cycle is a strong increasing function of recuperator effectiveness as shown in Figures 4 and 5. It should be noted that the heat transfer area required to produce a given effectiveness increases in a highly nonlinear manner as the effectiveness approaches 1.0. For example, the heat exchanger area approximately doubles in going from 90 to 95 percent effectiveness, it doubles again in going from 95 to 98 percent, and it doubles again going from 98 to 99 percent. A 100 percent effectiveness requires an infinite heat exchanger.

Turbine Inlet Temperature

Brayton cycle efficiency is also a strongly increasing function of turbine inlet temperature as seen in Figures 4 through 10. Present technology limits the allowable inlet temperature in closed cycles to about 1089-1255°K (1500-1800°F), while that of open cycles can be as high as 1255-1644°K (1800-2500°F).

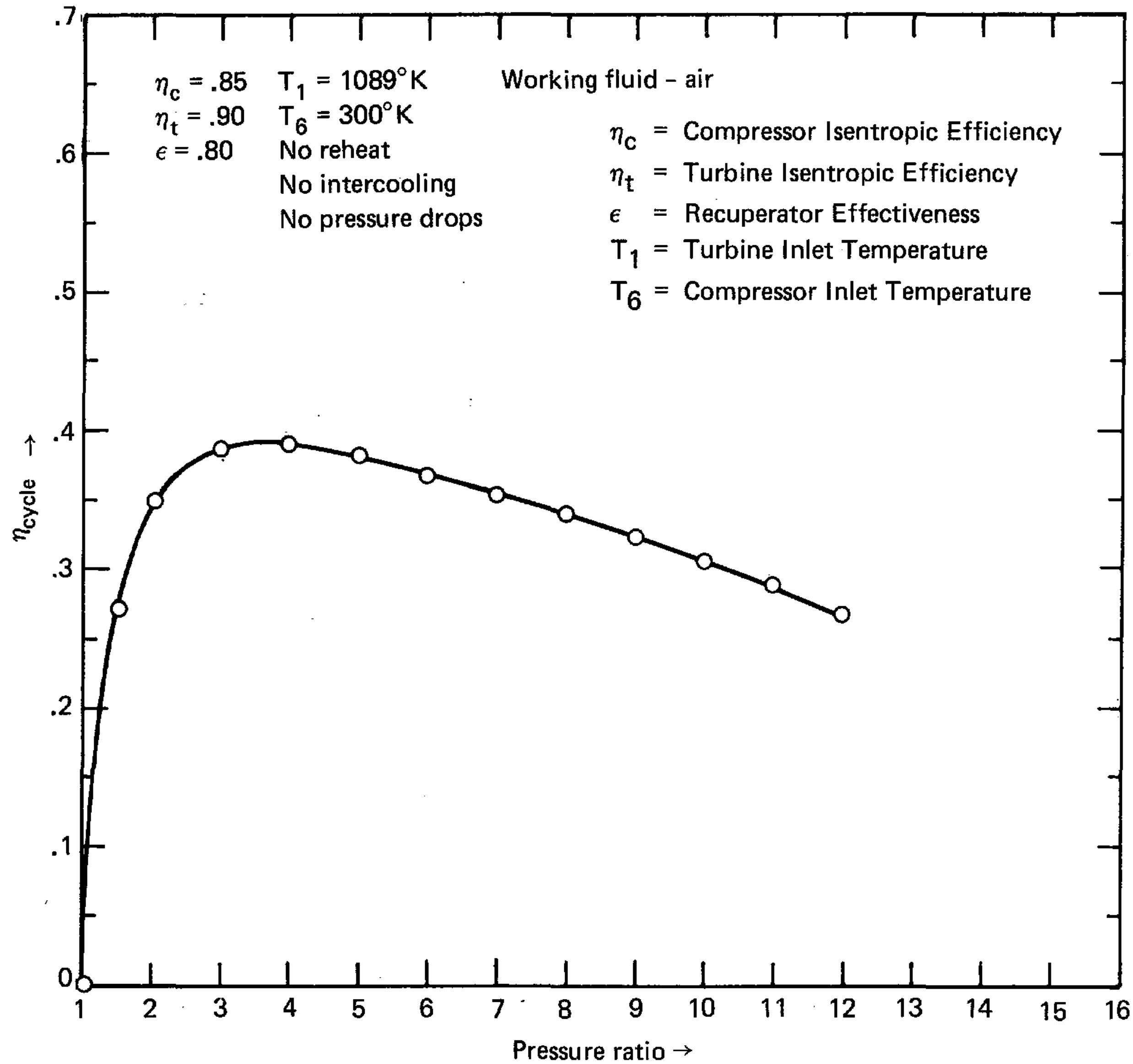

Figure 2. Effect of Pressure Ratio on Cycle Efficiency

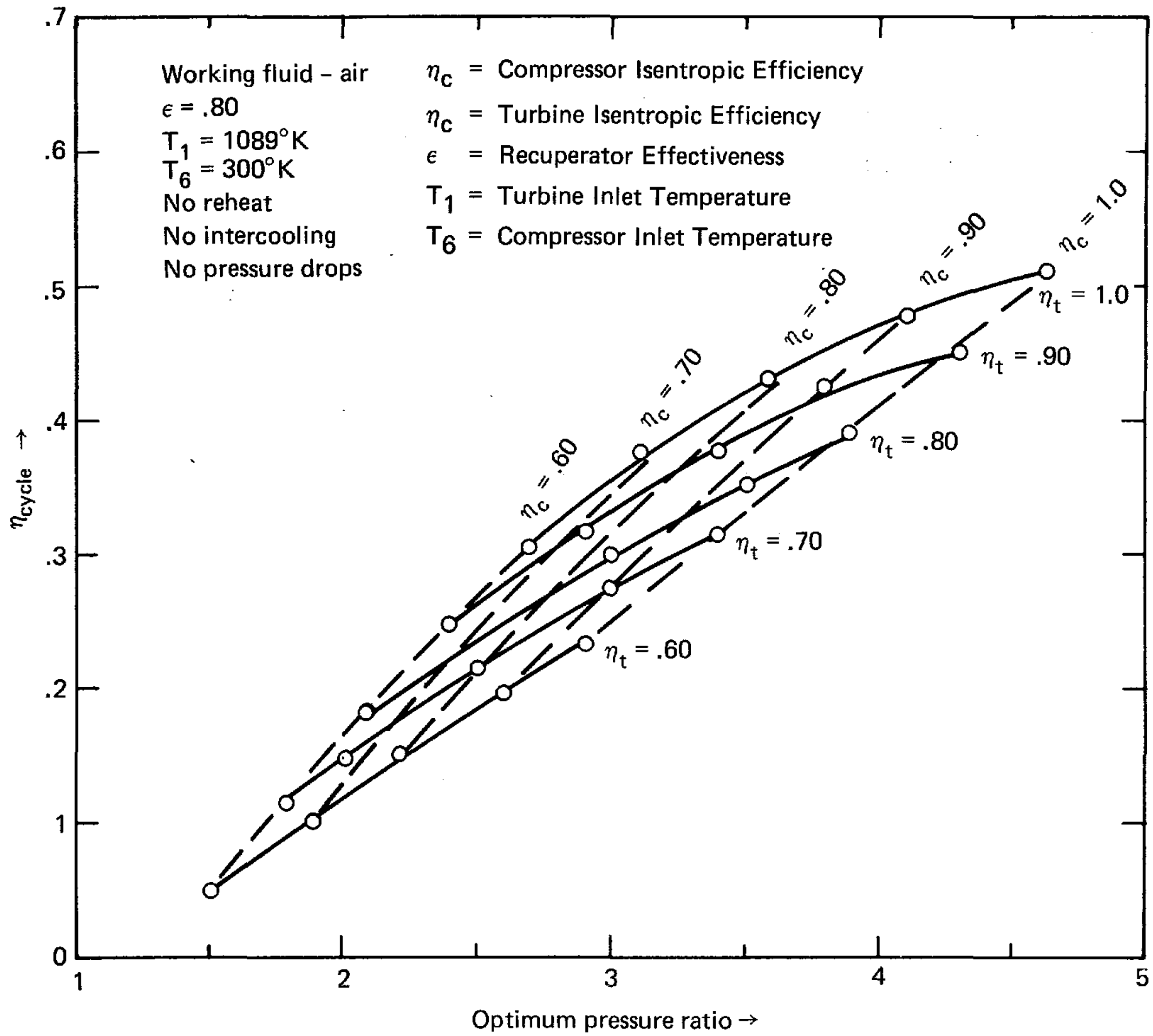

Figure 3. Variation of Cycle Efficiency and Optimum Pressure Ratio With Turbine and Compressor Efficiency

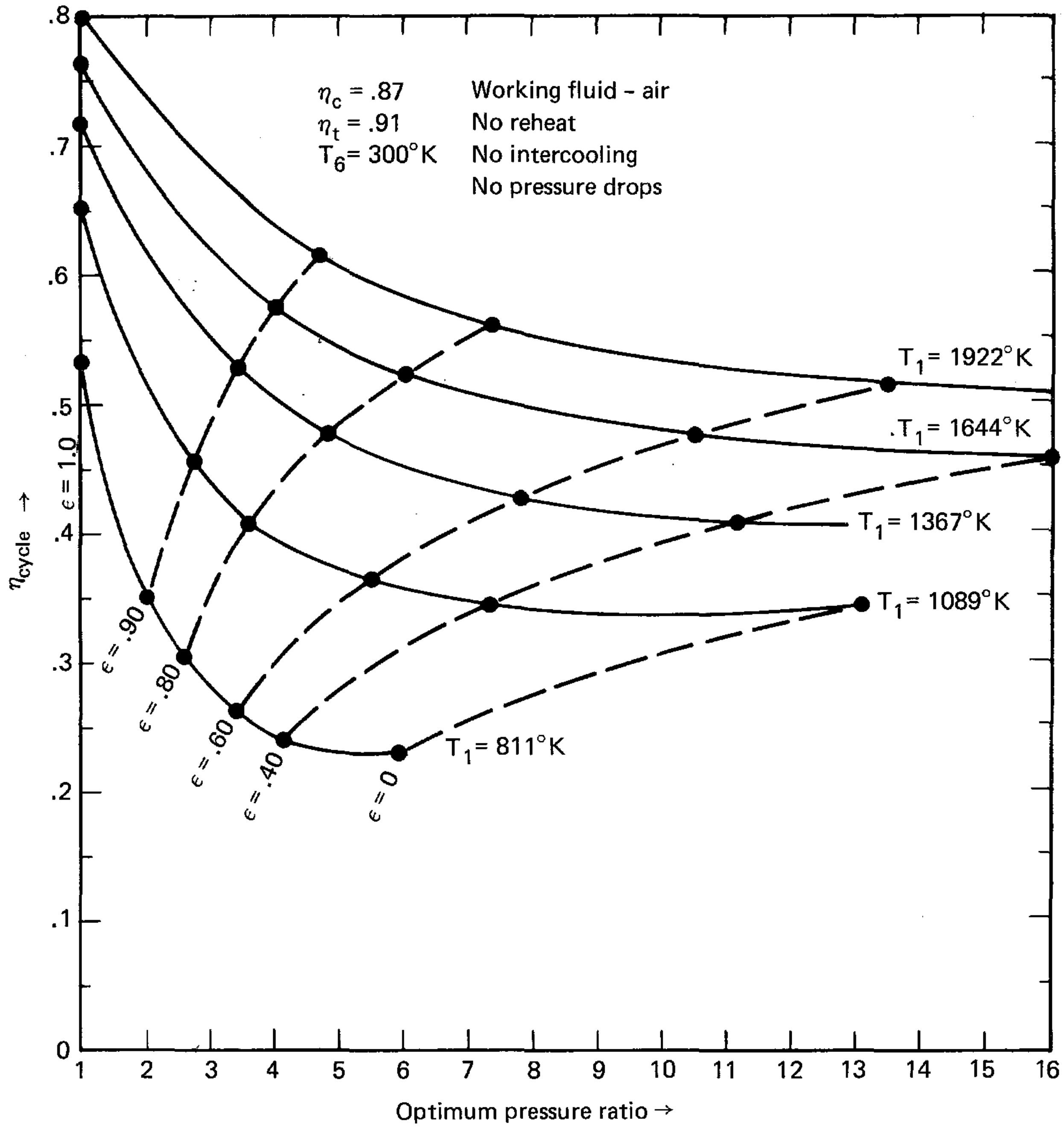

Figure 4. Variation of Air Cycle Efficiency and Optimum Pressure Ratio With Recuperator Effectiveness and Turbine Inlet Temperature

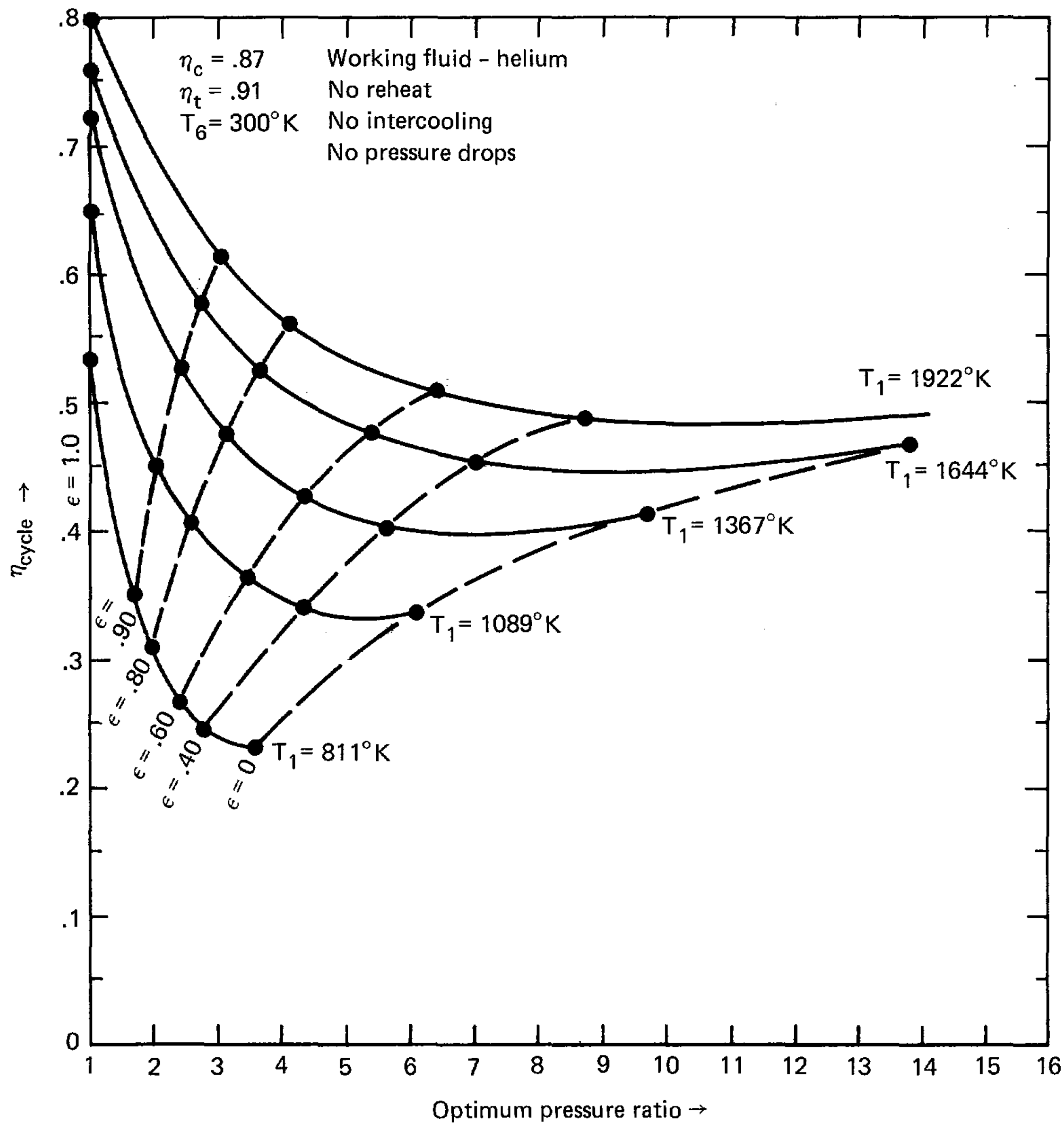

Figure 5. Variation of Helium Cycle Efficiency and Optimum Pressure Ratio With Recuperator Effectiveness and Turbine Inlet Temperature

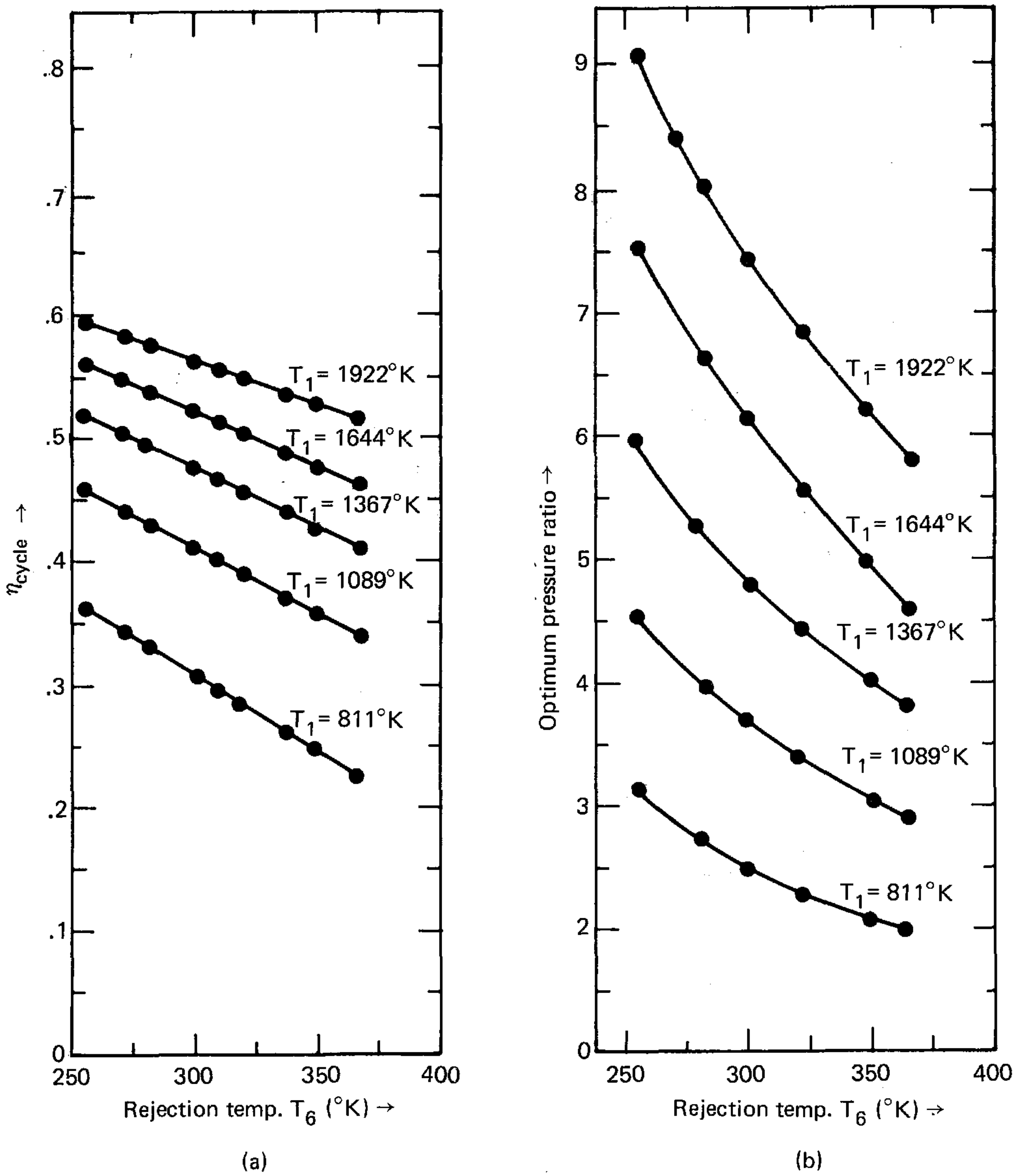

Figure 6. Effect of Rejection Temperature T_6 on Cycle Efficiency and Optimum Pressure Ratio

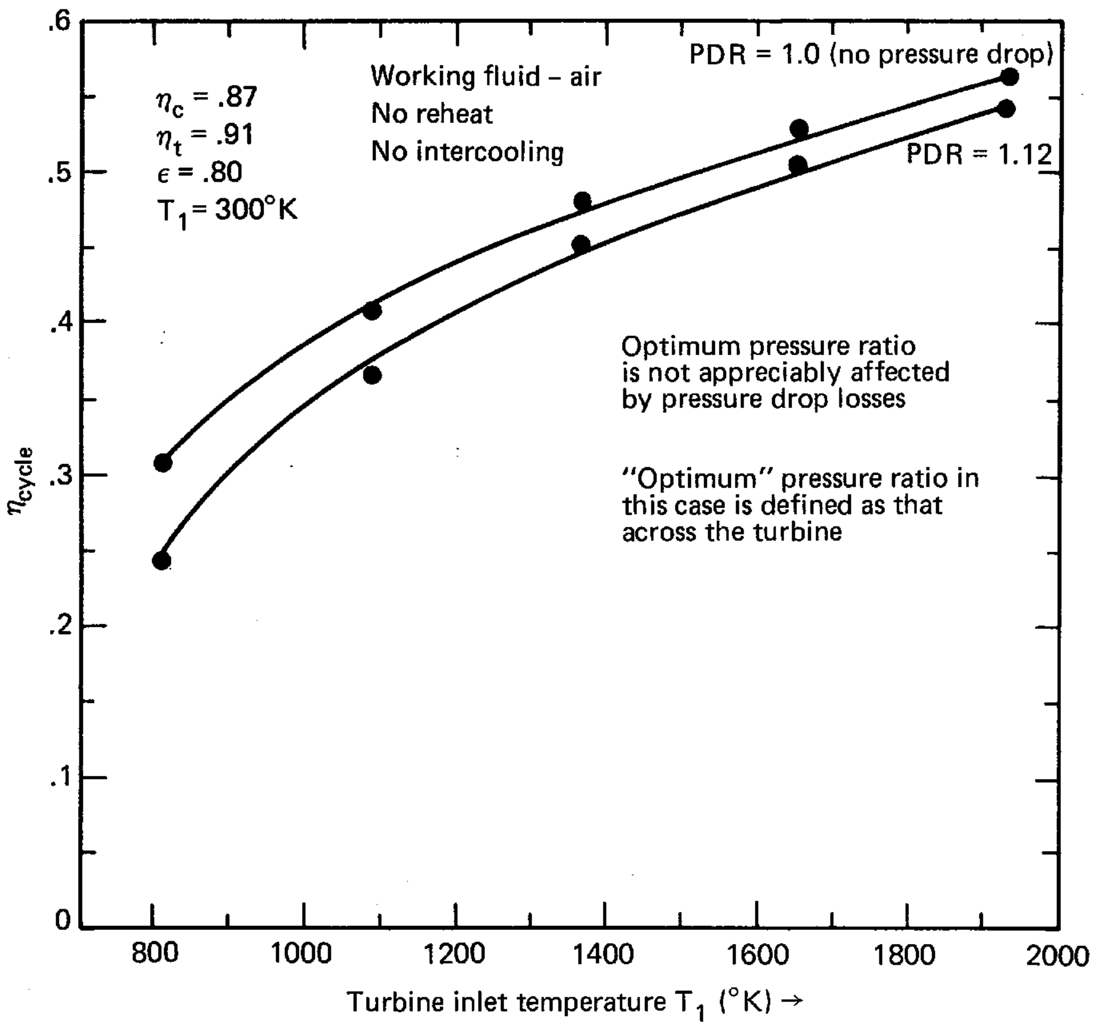

Figure 7. Effect of Pressure Drop Losses on Cycle Efficiency

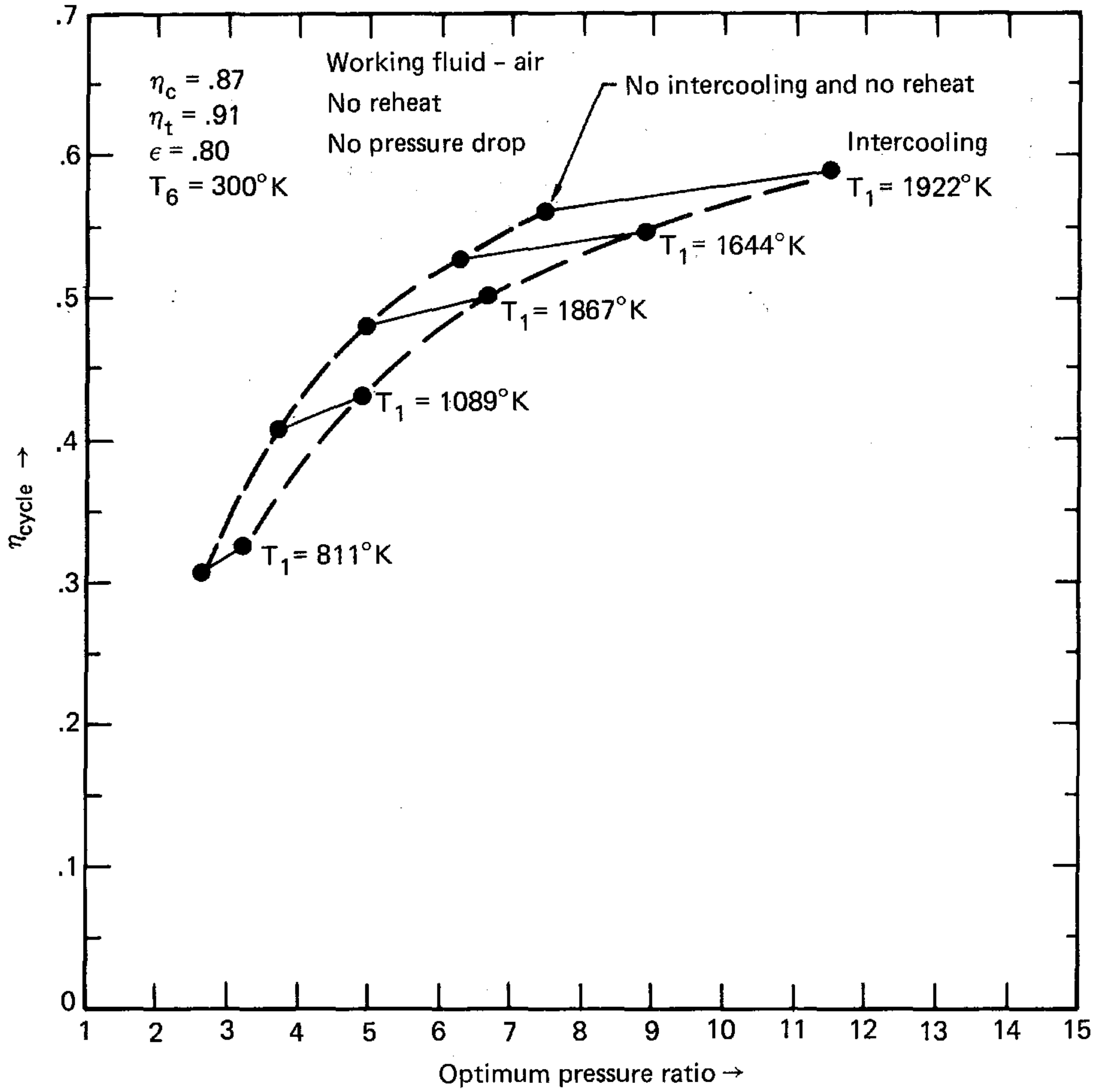

Figure 8. Effect of Intercooling on Cycle Efficiency and Optimum Pressure Ratio

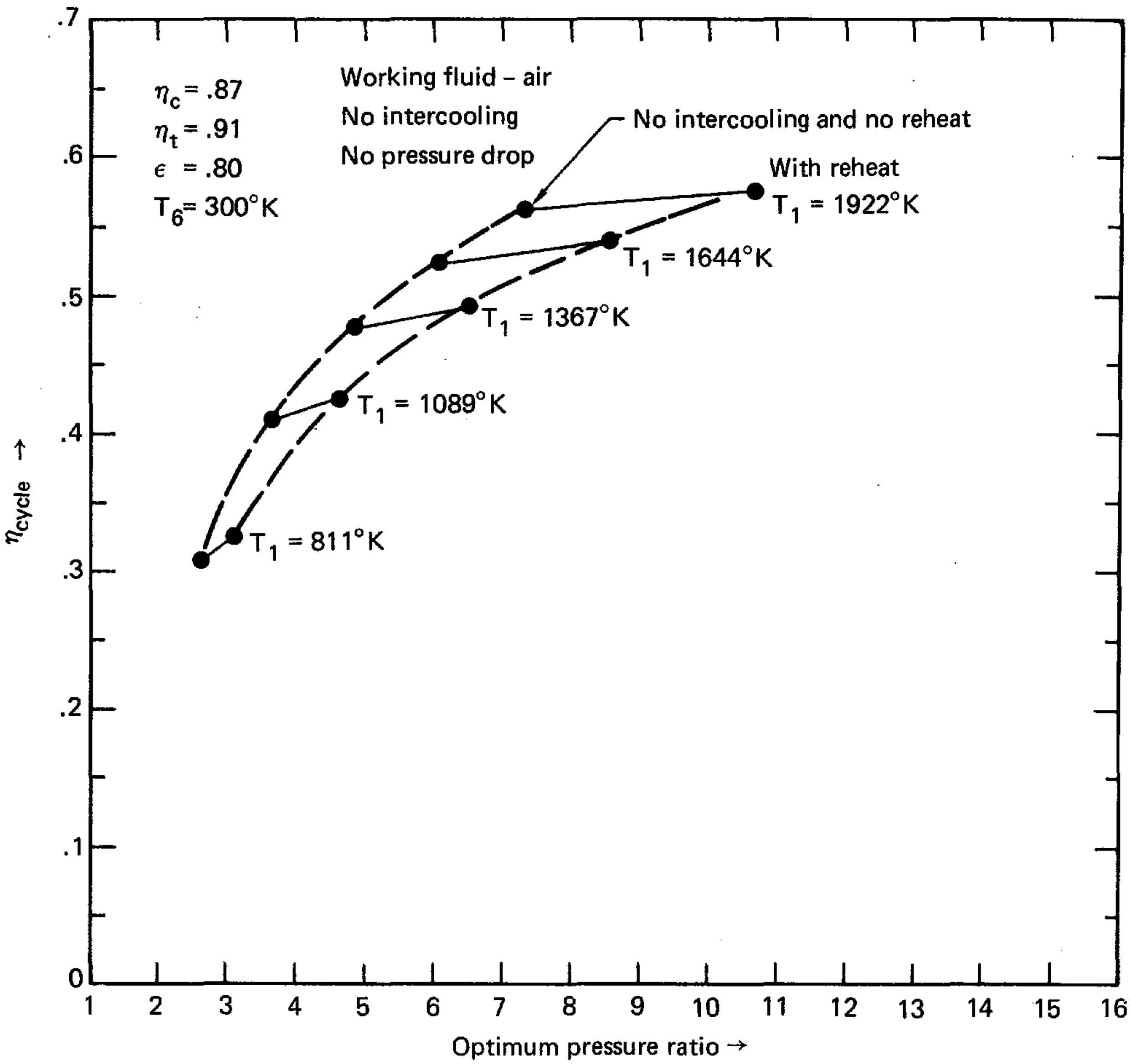

Figure 9. Effect of Reheat on Cycle Efficiency and Optimum Pressure Ratio

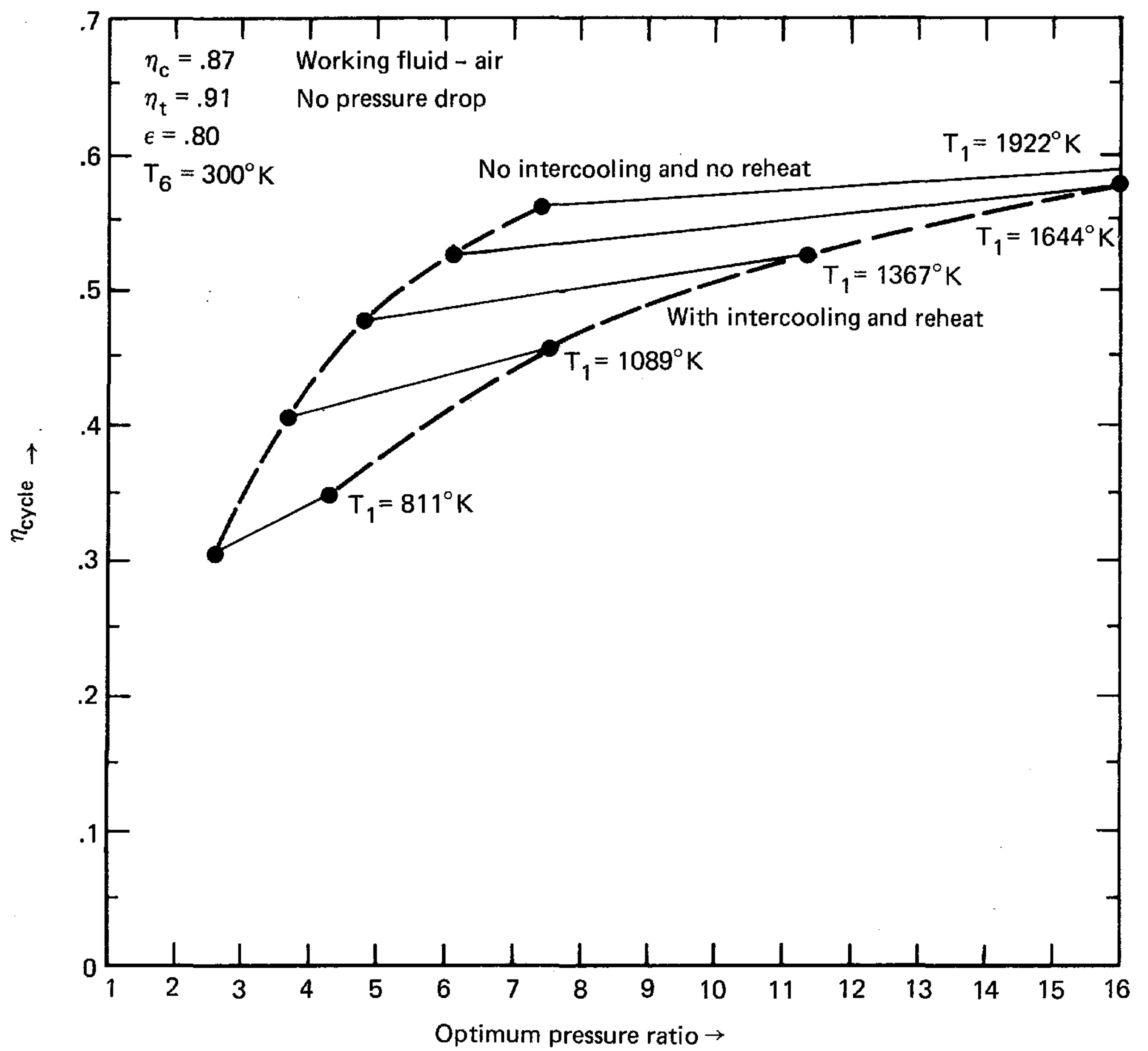

Figure 10. Combined Effects of Intercooling and Reheat

Turbine designers are currently attempting to develop better blade cooling techniques and ceramic blades which will allow reliable operation at inlet temperatures 1922°K (3000°F) or higher. However, improvements have historically been achieved slowly and in small increments.

Heat Rejection Temperature

The temperature at which heat is rejected from the cycle also has a strong effect on cycle efficiency as shown in Figure 6. This effect is usually less apparent than some other effects because the normal temperature range over which heat is rejected is small. However, the effect is very important when considering total energy applications where the rejected heat must be at fairly high temperature for use in another process, such as district heating. The models given in the appendices may be used to study sets of parameters other than those shown in Figure 6.

Pressure Drop Losses

Pressure drops caused by flow through heat exchangers, piping, and other components always reduce cycle efficiency. This drop in efficiency appears as an increase in the pressure ratio across which the compressor must pump relative to the turbine. In the present model this effect can be adequately represented by a parameter defined as the "Pressure Drop Ratio" (PDR).

$$\text{PDR} = \frac{\text{Pressure Ratio Across Compressor}}{\text{Pressure Ratio Across Turbine}}$$

Figure 7 shows the effect of pressure drop losses on cycle efficiency. The indicated range of PDR = 1.0 (no pressure drop) to PDR = 1.12 represents the normal range of pressure drops one would expect to encounter, and efficiency varies roughly linearly between the extremes. The models given in the appendices may be used to study the effect of pressure drops under sets of parameters other than shown in Figure 7.

Staged Compression with Intercooling

Staged compression with intercooling between stages reduces the required compressor work and improves heat transfer in the recuperator, which results in a net gain in cycle efficiency. Figure 8 shows the gain in efficiency due to a single stage of intercooling, assuming the fluid entering the second stage compressor is cooled to the same temperature as that entering the first stage. Of course, the additional heat exchangers and compressors for multistage compression with intercooling increase system cost and complexity, and therefore their value must be judged for each application.

Multiple Expansion with Reheat

Multiple-stage expansion with reheat between stages raises the average expansion temperature in the turbine, increasing turbine work output per unit of working fluid, and thus raising cycle efficiency. Figure 9 shows the gain in efficiency due to a single stage of reheat, assuming the inlet temperature to the second stage is the same as for the first stage. Reheat requires greater use of expensive high-temperature materials and reduces reliability because of the additional components. The desirability of reheat must hence be examined for each application. Figure 10 shows the combined gains due to intercooling and reheat. The models given in the appendices may be used to study the benefits under other sets of parameters.

Other Factors Affecting Efficiency

Several other factors affect the design point efficiency of Brayton cycle power plants, such as heat input efficiency, generator efficiency, and auxiliary power requirements. Auxiliary power requirements, such as fans for cooling towers, are typically of the order of 3 or 4 percent of the net output power. Large generator efficiency is typically around 98 percent, and heat input efficiency is frequently of the order of 89 percent. Thus, to obtain a more realistic value of plant efficiency, the values given in the figures of this report should be multiplied by $(0.98)(0.89)(1-0.03) = 0.85$.

Summary

This study has illustrated the sensitivity of Brayton cycle efficiency to a number of parameters. There is little that can be done to significantly change heat rejection temperature for a given application, but efforts should be made to optimize the other variables studied. For example, large gains can be realized if cost-effective means can be implemented to increase the turbine inlet temperature, increase recuperation effectiveness, or decrease pressure drops. Similarly, more emphasis should be placed on developing cost-effective intercooling and reheat cycles. In all cases, plants should be designed to operate at or near the optimum pressure ratio for their given design.

REFERENCES

1. Kuo, S. C., Horton, T. L. O., Shu, H. T., Seng, W. R., "The Prospects for Lightweight Ship Propulsion Systems," ASME Preprint No. 78-GT-179, December 28, 1977.

2. Bloomfield, H. S. and Calogeras, J. E., Technical and Economic Feasibility Study of Solar/Fossil Hybrid Power Systems, NASA Technical Memorandum NASA TM-73820, December 1977.

3. Boeing Engineering and Construction, Closed Cycle, High-Temperature Central Receiver Concept for Solar Electric Power, Final Technical Report Research Project 377-1 for Electrical Power Research Institute.

4. Hiller, Carl C., An Introductory Comparison of Brayton and Rankine Power Cycles for Central Solar Power Generation, SAND78-8010, May 1978.

APPENDIX A

DERIVATIONS FOR BRAYTON PLANT MODEL

Figures A-1 and A-2 show the plant configuration for which the present model has been developed.

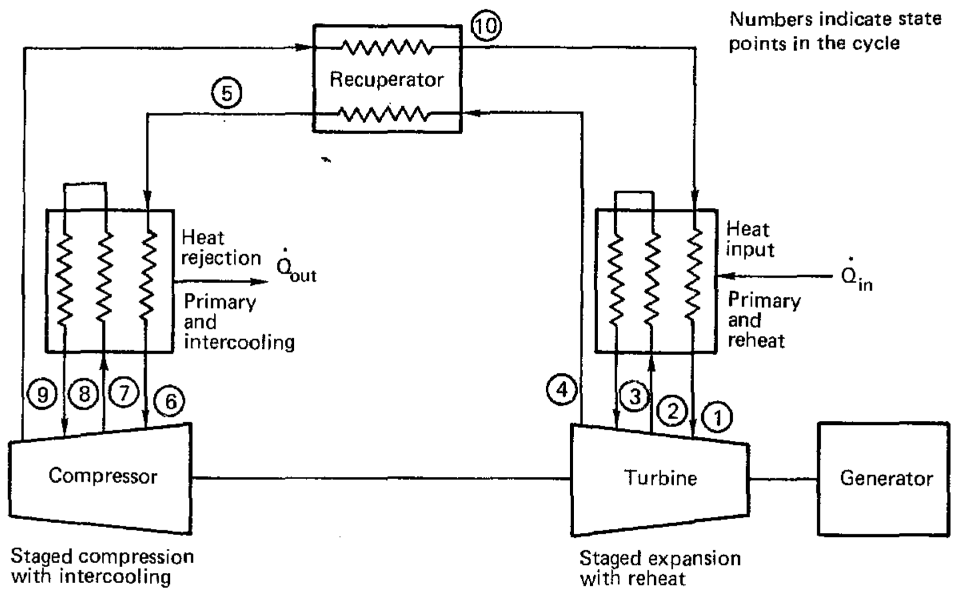

Figure A-1. Brayton Cycle Power Plant

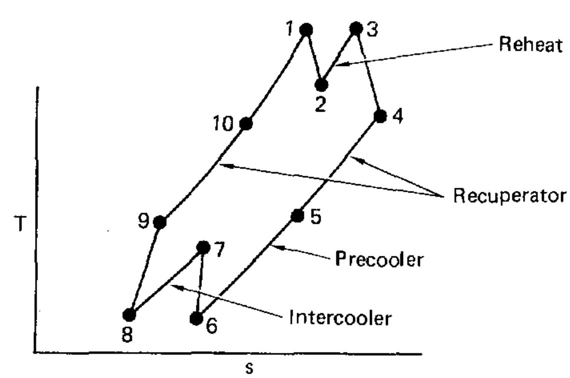

Figure A-2. Thermodynamic Cycle

Assuming ideal gas

$$C_p = \text{constant}$$

$$\gamma = \frac{C_p}{C_p - R} = \text{constant}$$

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} \quad \text{for an isentropic process}$$

$$\left[\frac{\dot{W}_t}{\dot{m}}\right]_{1-2} = C_p(T_1 - T_2) = C_p\eta_t(T_1 - T_{2_{ISENTROPIC}}) \qquad \text{turbine}$$

$$\left[\frac{\dot{W}_t}{\dot{m}}\right]_{3-4} = C_p(T_3 - T_4) \qquad \text{turbine}$$

$$\left[\frac{\dot{W}_c}{\dot{m}}\right]_{6-7} = C_p(T_7 - T_6) = \frac{C_p}{\eta_c}(T_{7_{ISENTROPIC}} - T_6) \qquad \text{compressor}$$

$$\left[\frac{\dot{W}_c}{\dot{m}}\right]_{8-9} = C_p(T_9 - T_8) \qquad \text{compressor}$$

$$T_2 = T_1\left\{1 - \eta_t\left[1 - \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}\right]\right\}$$

$$T_4 = T_3\left\{1 - \eta_t\left[1 - \left(\frac{P_4}{P_3}\right)^{\frac{\gamma-1}{\gamma}}\right]\right\}$$

$$T_7 = T_6\left\{1 + \frac{1}{\eta_c}\left[\left(\frac{P_7}{P_6}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]\right\}$$

$$T_9 = T_8\left\{1 + \frac{1}{\eta_c}\left[\left(\frac{P_9}{P_8}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]\right\}$$

η_t = turbine isentropic efficiency

η_c = compressor isentropic efficiency

$$T_5 = T_4 - \epsilon(T_4 - T_9)$$

$$T_{10} = T_9 + \epsilon(T_4 - T_9)$$

ϵ = Recuperator Effectiveness

$$\left[\frac{W}{m}\right]_{NET} = \left[\frac{W_t}{m}\right]_{1-2} + \left[\frac{W_c}{m}\right]_{3-4} - \left[\frac{W_c}{m}\right]_{6-7} - \left[\frac{W_c}{m}\right]_{8-9}$$

$$\left[\frac{Q}{m}\right]_{IN} = C_p(T_1 - T_{10}) + C_p(T_3 - T_2)$$

Then

$$\eta_{CYCLE} = \frac{\left[\frac{W}{m}\right]_{NET}}{\left[\frac{Q}{m}\right]_{IN}} = \frac{(T_1 - T_2) + (T_3 - T_4) - (T_7 - T_6) - (T_9 - T_8)}{(T_1 - T_{10}) + (T_3 - T_2)}$$

If we wish to account for heat input efficiency, generator efficiency, and auxiliaries we have

$$\left[\frac{W}{m}\right]_{\substack{NET\\ACTUAL}} = \left[\frac{W}{m}\right]_{NET} \eta_G(1 - F_{AUX})$$

η_G = Generator Efficiency

F_{AUX} = Fraction of the output power required to run auxiliaries (such as cooling tower fans)

$$\left[\frac{Q}{m}\right]_{\substack{IN\\ACTUAL}} = \frac{\left[\frac{Q}{m}\right]_{IN}}{\eta_B}$$

η_B = Boiler or heat input efficiency

Then

$$\eta_{\substack{CYCLE\\ACTUAL}} = \eta_G \eta_B (1 - F_{AUX}) \frac{\left[T_1 + T_3 + T_6 + T_8 - T_2 - T_4 - T_7 - T_9\right]}{T_1 + T_3 - T_{10} - T_2}$$

Notes:

1. We have assumed one stage of intercooling and one stage of reheat with

$$\frac{P_9}{P_8} = \frac{P_7}{P_6}, \quad \frac{P_1}{P_2} = \frac{P_3}{P_4}, \quad T_3 = T_1, \text{ and } T_8 = T_6.$$ If no intercooling or reheat is desired, set $T_3 = T_2$, $T_8 = T_6$, $\frac{P_1}{P_2} = 1$, and $\frac{P_6}{P_7} = 1$.

2. Pressure drop losses in the system can be accounted for by varying the net pressure ratio across the turbines relative to that across the compressors using the variable

$$\underset{\text{(Pressure Drop Ratio)}}{\text{PDR}} = \frac{\text{Press. Ratio Across Comp.}}{\text{Press. Ratio Across Turb.}}$$

3. If no recuperator is desired, set $\epsilon = 0$.

4. The model correctly simulates both open and closed cycles because it uses pressure ratios rather than absolute pressures.

APPENDIX B

COMPUTER PROGRAM FOR BRAYTON CYCLE PERFORMANCE

Described here is a FORTRAN program for computing Brayton cycle efficiency using real-time interactive data input through namelists.

Input parameters are

Computer Symbol	Parameter
GAMA	γ
EFFT	η_t
EFFC	η_c
EFFG	η_g
FAUX	F_{AUX}
EFFB	η_B
T1	T_1
T6	T_6
T3	T_3
T8	T_8
ERCUP	ϵ
PR	PR
PDR	PDR
MODE	MODE

Calculated outputs are

Computer Symbol	Parameter
T2	T_2
T4	T_4
T5	T_5
T7	T_7
T9	T_9
T10	T_{10}
EFF	$\eta_{CYCLE\ ACTUAL}$
PRT	$PR_{TURBINE}$
PRC	$PR_{COMPRESSOR}$

PROGRAM LISTING

```
      PROGRAM ADV8(INPUT,OUTPUT,TAPE1=OUTPUT)
C ADVANCED BRAYTON CYCLE POWER PLANT EFFICIENCY PROGRAM
      NAMELIST/COEF/GAMA,EFFT,EFFC,EFFG,FAUX,EFFB
      NAMELIST/PARAM/T1,T6,T3,T8,ERCUP,PR,PDR,MODE
C MODE 1-REHEAT,INTER, 2-REHEAT ONLY, 3-INTER ONLY, 4-NEITHER
C DEFAULT VALUES
      T6=305.2
      IWRITE=1
      PDR=1.
      EFFT = .91
      EFFC = .87
      EFFG = .982
      FAUX = .036
      DO 2000 IRUN=1,500
      EFF = 0.
      DATA T1,T2,T3,T4,T5,T7,T8,T9,T10/
     10.,0.,0.,0.,0.,0.,0.,0.,0./
      WRITE(IWRITE,800)
800   FORMAT(≠ NAMELIST - COEF, GAMA,EFFT,EFFC,EFFG,FAUX,EFFB≠)
      READ COEF
      WRITE(IWRITE,810)
810   FORMAT(≠ NAMELIST - PARAM,T1,T6,T3,T8,ERCUP,PR,PDR,MODE≠)
      READ PARAM
      XK = (GAMA-1.)/GAMA
      T3=T1
      T8=T6
      IF(MODE.EQ.1) GO TO 400
      IF(MODE.EQ.2) GO TO 300
      IF(MODE.EQ.3) GO TO 200
      IF(MODE.EQ.4) GO TO 100
      GO TO 2000
100   T3=T1
      T8=T6
      PRT=1.
      PRC=1.
      GO TO 600
200   T3=T1
      PRT=1.
      GO TO 500
300   T8=T6
      PRC=1.
400   PRT=SQRT(PR)
      IF(MODE.EQ.2) GO TO 600
500   PRC=SQRT(PDR*PR)
600   T2=T1*(1.-EFFT*(1.-(1./PRT)**XK))
      T4=T3*(1.-EFFT*(1.-(PRT/PR)**XK))
      T7=T6*(1.+(PRC**XK-1.)/EFFC)
      T9=T8*(1.+((PR*PDR/PRC)**XK-1.)/EFFC)
      T10=T9 + ERCUP*(T4-T9)
      T5= T4 - ERCUP*(T4-T9)
      EFF=EFFB*(1.-FAUX)*EFFG*(T1+T3+T6+T8-T2-T4-T7-T9)/
     1(T1+T3-T2-T10)
      WRITE(IWRITE,850)
      WRITE(IWRITE,820) GAMA,EFFT,EFFC,EFFG,FAUX
```

```
      WRITE(IWRITE,840)
      WRITE(IWRITE,820)  ERCUP,PR,PRT,PRC,EFFB
      WRITE(IWRITE,830)
      WRITE(IWRITE,820)  T1,T2,T3,T4,T5
      WRITE(IWRITE,860)
      WRITE(IWRITE,820)  T6,T7,T8,T9,T10
      WRITE(IWRITE,870)
      WRITE(IWRITE,880)  MODE,PDR,EFF
      PAUSE
2000  CONTINUE
820   FORMAT(5F10.3)
830   FORMAT(≠ T1,T2,T3,T4,T5≠)
840   FORMAT(≠ ERCUP,PR,PRT,PRC,EFFB≠)
850   FORMAT(≠ GAMA,EFFT,EFFC,EFFG,FAUX≠)
860   FORMAT(≠ T6,T7,T8,T9,T10≠)
870   FORMAT(≠ MODE,PDR,EFF≠)
880   FORMAT(I5,2F10.3)
      END
```

SAMPLE OUTPUT

```
NAMELIST - COEF, GAMA,EFFT,EFFC,EFFG,FAUX,EFFB
NAMELIST - PARAM,T1,T6,T3,T8,ERCUP,PR,PDR,MODE
GAMA,EFFT,EFFC,EFFG,FAUX
    1.670      .910      .870      .980     0.000
ERCUP,PR,PRT,PRC,EFFB
     .950     1.790     1.000     1.000      .890
T1,T2,T3,T4,T5
 1089.000  1089.000  1089.000   882.568   449.413
T6,T7,T8,T9,T10
  322.000   322.000   322.000   426.615   859.771
MODE,PDR,EFF
    4     1.039      .387
```

PAUSE GO

```
NAMELIST - COEF, GAMA,EFFT,EFFC,EFFG,FAUX,EFFB
NAMELIST - PARAM,T1,T6,T3,T8,ERCUP,PR,PDR,MODE
GAMA,EFFT,EFFC,EFFG,FAUX
    1.670      .910      .870      .980     0.000
ERCUP,PR,PRT,PRC,EFFB
     .950     1.790     1.000     1.000      .890
T1,T2,T3,T4,T5
 1089.000  1089.000  1089.000   882.568   453.220
T6,T7,T8,T9,T10
  322.000   322.000   322.000   430.623   859.971
MODE,PDR,EFF
    4     1.061      .372
```

PAUSE STOP

APPENDIX C

HAND CALCULATOR PROGRAM FOR DETERMINING BRAYTON CYCLE EFFICIENCY

The following program has been developed for use on a Hewlett-Packard Model 67 calculator.

η_c $\uparrow$	γ $\uparrow$	PR $\boxed{C}$	
η_t $\uparrow$	PDR $\uparrow$		Brayton Cycle Program
ϵ $\uparrow$	T_1 $\uparrow$		
Mode $\boxed{A}$	T_6 $\boxed{B}$	Computes	
Initialize	Initialize	η_{CYCLE}	

$\boxed{A}$	$\boxed{B}$	$\boxed{C}$	$\boxed{D}$	$\boxed{E}$

Suggested Magnetic Card Labels

<u>Operating Procedures</u>

Variable	Keystroke	Operation
η_c	Enter	
η_t	Enter	
ϵ	Enter	
Mode	A	Stores Values
γ	Enter	
PDR	Enter	
T_1	Enter	
T_6	B	Stores values and computes $\frac{\gamma-1}{\gamma}$
PR	C	Computes and returns η_{CYCLE}

Notes:

Values in either the A or B columns may be varied without re-entering the other column, and PR can be varied without changing the A and B columns.

Examples:

Let η_c = 0.8

η_t = 0.9

ϵ = 0.8

Mode = 4

γ = 1.4

PDR = 1.0

T_1 = 1089°K

T_6 = 300°K

PR = 2.0, 2.2, and 2.4

Press		Display		
.8	Enter	.80		
.9	Enter	.90		
.8	Enter	.80		
4	A	.80		
1.4	Enter	1.40		
1	Enter	1.00		
1089	Enter	1089.00		
300	B	.2857		
2	C	.3329	(η_{CYCLE})	γ = 14
2.2	C	.3466	(η_{CYCLE})	
2.4	C	.3559	(η_{CYCLE})	ϵ = 0.80

Now change ϵ to 0.95

Press		Display		
.8	Enter	.80		
.9	Enter	.90		
.95	Enter	.95		
4	A	.80		
2	C	.4637	(η_{CYCLE})	$\gamma = 1.4$
2.2	C	.4626	(η_{CYCLE})	
2.4	C	.4594	(η_{CYCLE})	$\epsilon = 0.95$

Now change γ to 1.67

Press		Display		
1.67	Enter	1.67		
1	Enter	1.00		
1089	Enter	1089.00		
300	B	.4012		
2	C	.4536	(η_{CYCLE})	$\gamma = 1.67$
2.2	C	.4430	(η_{CYCLE})	
2.4	C	.4311	(η_{CYCLE})	$\epsilon = 0.95$

It should also be noted that the temperatures in the cycle as shown in Figure A-1 are calculated and stored in the protected storage registers of the same number with the exception of T_5; i.e., T_1 is in protected register 1, T_7 is in protected register 7, T_{10} is in protected register 0, and so forth.

PROGRAM LISTING

```
001  *LBLA      21 11
002  STOA       35 11
003  R↓           -31
004  STOB       35 12
005  R↓           -31
006  STOC       35 13
007  R↓           -31
008  STOD       35 14
009  RTN           24
010  *LBLB      21 12
011  P⇄S        16-51
012  STO6       35 06
013  R↓           -31
014  STO1       35 01
015  R↓           -31
016  STOE       35 15
017  R↓           -31
018  1             01
019  9             09
020  STOI       35 46
021  X⇄Y          -41
022  STOi       35 45
023  1             01
024  -            -45
025  RCLi       36 45
026  ÷            -24
027  STOi       35 45
028  P⇄S        16-51
029  RTN           24
030  *LBLC      21 13
031  P⇄S        16-51
032  1             01
033  8             08
034  STOI       35 46
035  X⇄Y          -41
036  STO5       35 05
037  RCL1       36 01
038  STO3       35 03
039  RCL6       36 06
040  STO8       35 08
041  1             01
042  RCLA       36 11
043  X=Y?       16-33
044  GTO1       22 01
045  2             02
046  RCLA       36 11
047  X=Y?       16-33
048  GTO2       22 02
049  3             03
050  RCLA       36 11
051  X=Y?       16-33
052  GTO3       22 03
053  4             04
054  RCLA       36 11
055  X=Y?       16-33
056  GTO4       22 04
057  GTO9       22 09
058  *LBL4      21 04
059  RCL1       36 01
060  STO3       35 03
061  RCL6       36 06
062  STO8       35 08
063  1             01
064  STOi       35 45
065  DSZI    16 25 46
066  STOi       35 45
067  GTO8       22 08
068  *LBL3      21 03
069  RCL1       36 01
070  STO3       35 03
071  1             01
072  STOi       35 45
073  GTO7       22 07
074  *LBL2      21 02
075  RCL6       36 06
076  STO8       35 08
077  DSZI    16 25 46
078  1             01
079  STOi       35 45
080  ISZI    16 26 46
081  SF0     16 21 00
082  *LBL1      21 01
083  RCL5       36 05
084  √X            54
085  STOi       35 45
086  F0?     16 23 00
087  GTO8       22 08
088  *LBL7      21 07
089  RCL5       36 05
090  RCLE       36 15
091  ×            -35
092  √X            54
093  DSZI    16 25 46
094  STOi       35 45
095  *LBL8      21 08
096  1             01
097  7             07
098  F0?     16 23 00
099  STOI       35 46
100  CF0     16 22 00
101  ISZI    16 26 46
102  RCLi       36 45
103  1/X           52
104  ISZI    16 26 46
105  RCLi       36 45
106  Y^X           31
107  1             01
108  X⇄Y          -41
109  -            -45
110  RCLC       36 13
111  ×            -35
112  1             01
113  X⇄Y          -41
114  -            -45
115  RCL1       36 01
116  ×            -35
117  STO2       35 02
118  RCLi       36 45
119  DSZI    16 25 46
120  RCLi       36 45
121  RCL5       36 05
122  ÷            -24
123  X⇄Y          -41
124  Y^X           31
125  1             01
126  X⇄Y          -41
127  -            -45
128  RCLC       36 13
129  ×            -35
130  1             01
131  X⇄Y          -41
132  -            -45
133  RCL3       36 03
134  ×            -35
135  STO4       35 04
136  ISZI    16 26 46
137  RCLi       36 45
138  DSZI    16 25 46
139  DSZI    16 25 46
140  RCLi       36 45
141  X⇄Y          -41
142  Y^X           31
143  1             01
144  -            -45
145  RCLD       36 14
146  ÷            -24
147  1             01
148  +            -55
149  RCL6       36 06
150  ×            -35
151  STO7       35 07
152  RCL5       36 05
153  RCLE       36 15
154  ×            -35
155  RCLi       36 45
156  ÷            -24
157  ISZI    16 26 46
158  ISZI    16 26 46
159  RCLi       36 45
160  Y^X           31
161  1             01
162  -            -45
163  RCLD       36 14
164  ÷            -24
165  1             01
166  +            -55
167  RCL8       36 08
168  ×            -35
169  STO9       35 09
170  RCL4       36 04
171  X⇄Y          -41
172  -            -45
173  RCLB       36 12
174  ×            -35
175  RCL9       36 09
176  +            -55
177  STO0       35 00
178  RCL1       36 01
179  RCL3       36 03
180  +            -55
181  RCL6       36 06
182  +            -55
183  RCL8       36 08
184  +            -55
185  RCL2       36 02
186  -            -45
187  RCL4       36 04
188  -            -45
189  RCL7       36 07
190  -            -45
191  RCL9       36 09
192  -            -45
193  RCL1       36 01
194  RCL3       36 03
195  +            -55
196  RCL2       36 02
197  -            -45
198  RCL0       36 00
199  -            -45
200  ÷            -24
201  P⇄S        16-51
202  RTN           24
203  *LBL9      21 09
204  1             01
205  0             00
206  0             00
207  10^X       16 33
208  P⇄S        16-51
209  RTN           24
210  R/S           51
```

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