NASA -TM -82960

DOE/NASA/51040-42
NASA TM-82960

NASA-TM-82960

Computer Program for Stirling Engine Performance Calculations

Roy C. Tew, Jr.
National Aeronautics and Space Administration
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January 1983

Prepared for
U.S. DEPARTMENT OF ENERGY
Conservation and Renewable Energy
Office of Vehicle and Engine R&D

NOTICE

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The attached tables VII, VIII, and IX should be included in the report.

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Office of Vehicle and Engine R&D
Washington, D.C. 20545
Under Interagency Agreement DE-AI01-77CS51040

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I. ABSTRACT

To support the development of the Stirling engine as a possible alternative to the automobile spark-ignition engine, the thermodynamic characteristics of the Stirling engine were analyzed and modeled on a computer. The computer model is documented. The documentation includes a user's manual, symbols list, a test case, comparison of model predictions with test results, and a description of the analytical equations used in the model.

II. INTRODUCTION

The Stirling engine is being developed as a possible alternative to the spark-ignition engine under the Department of Energy's Stirling Engine Highway Vehicle Systems Program. NASA Lewis Research Center has project management responsibility for the program.

A Stirling engine performance model has been developed at Lewis to support both the project management activities and the Stirling engine test program at Lewis. An early version of the model, published in reference 1, assumed fixed heater and cooler tube temperatures. The model was then expanded to include the coolant side of the cooler and used to make predictions for comparison with the single cylinder GPU-3 Stirling engine test results (ref. 2). More recently, variable specific heats, appendix gap pumping losses and adiabatic connecting ducts have been included in the model, and it has been used to simulate one of United Stirling of Sweden's P-40 (approx 40 kW) engines. This engine, which has four cylinders and double-acting pistons, is now being tested at Lewis. Some of the test results are reported in reference 3; this reference also compares a few of the P-40 model predictions with some of the test results. Additional test results and a description of the test facility are reported in reference 4.

This model predicts engine performance for a given set of engine operating conditions (i.e., mean pressure, boundary temperatures, and engine speed). One of the four engine working spaces is modeled, and the resultant power is multiplied by four (controls models such as the one documented in reference 5 require modeling all four working spaces). The working space model includes two pistons, the piston swept volumes - the expansion and compression spaces, three heat exchangers - heater, regenerator and cooler, and four connecting ducts. The pistons are positioned as functions of time according to the specified frequency. The working space is divided into appropriately sized control volumes for analysis. Flow resistances and heat transfer coefficients are calculated for each control volume at each time step over the engine cycle. Within each gas volume the continuity and energy equations are integrated with respect to time; a simplified momentum equation (pressure drop is a function of a friction factor and flow rate) and an equation of state are also used in the calculations.

This report documents the current version of the Lewis Stirling engine performance model. A user's manual, symbols list, a test case and comparison of model predictions with test results for the P-40 engine are included in the documentation.

III. MODEL DESCRIPTION

The United Stirling P-40 engine, for which the test case and other model predictions were generated, is shown schematically in figure 1. The model simulates the thermodynamics of one of the four engine working spaces. The engine parts whose dimensions define the working spaces of the engine are:

(1) the four pistons and four cylinders, connected in a square-four arrangement, as shown in the lower right corner schematic of Figure 1.

(2) the circular array of heater tubes, the heater head, which connect the hot ends of the cylinders (expansion spaces) and the regenerators.

(3) the eight regenerators (two per cylinder).

(4) the eight coolers (two per cylinder) which connect the regenerators with the cold ends of the cylinders (compression spaces).

(5) the four transition regions or connecting ducts per working space (expansion space-heater, heater regenerator, etc.).

The hot expansion volume over one piston (part of the blackened area in the lower right corner schematic of fig. 1) is connected via one quadrant of the circular heater tube array, two regenerators and two coolers to the cold compression space volume beneath an adjacent piston; this constitutes one of the four working spaces. The model, assuming the four working spaces contribute equal amounts of power, multiplies the power predicted for the one simulated working space by four.

The simulated working space was divided into control volumes as shown in Figure 2 for the test case. The model provides for one control volume each for the expansion space, compression space and the four connecting ducts (or, optionally, the connecting duct volumes may be lumped with the adjacent control volumes - thus neglecting the loss due to the adiabatic nature of the control volumes). For the test case, 3 heater, 5 regenerator, and 3 cooler control volumes were used. However, the heater and cooler may be divided into any number of equal sized control volumes. The regenerator may be divided into any odd number of equal-sized control volumes (the regenerator matrix temperature convergence method has been checked out only for an odd number). In addition, two (optional) isothermal appendix gap control volumes, one adjacent to the expansion space and one adjacent to the compression space, are available to evaluate appendix gap pumping losses. For all predictions discussed in this report, the 17 non-isothermal plus two isothermal appendix gap control volumes shown in Figure 2 were used in the model.

The basic computer model equations are applied to each of the control volumes. The temperatures, masses, heat transfer coefficients, flow rates, etc. for each of the control volumes and interfaces (except the appendix gap volumes and interfaces) are represented by dimensioned variable names in the computer model. The numbering procedure used for control volume and interface variable names is defined in figure 2. The circled numbers in figure 2 correspond to control volume variables. The numbers with solid arrows correspond to interface variables. Appendix gap interfaces are labeled with numbers 0 and 17, respectively (dashed arrows); however, appendix gap volume and interface variables are represented by unique nondimensioned names in the computer model.

The model has recently been generalized to allow changing the number of heater, regenerator or cooler control volumes by resetting the appropriate parameters. Preliminary results of changing the number of control volumes are summarized in table I. It is seen that increasing the number of control volumes increases the value of the predicted power. It also increases the value of regenerator effectiveness and the required computer time (regenerator effectiveness, as used in this model, is defined in table IX).

Increasing the number of control volumes should increase the accuracy of the model, since variables which change continuously along the working space are being approximated by lumped parameters which change discontinuously from one control volume to another. However, increasing the number of control volumes costs additional computing time. Also the model already overpredicts power and efficiency for the P-40 engine with the control volume configuration of figure 2. Additional runs are needed to define how the number of control volumes affects the trade-off between computing time and accuracy. For the purpose of this documentation the 17 nonisothermal plus 2 isothermal control volumes, as shown in figure 2, were used.

The required engine operating conditions which must be input to the model are - heater tube outside wall temperatures (the combustor is not modeled), expansion and compression space inside wall temperatures, cooling water inlet temperature, cooling water flow rate, engine speed, and mean pressure. The cooler tube inside wall temperature is solved for by iteration but is constant for any one cycle. The only wall temperatures which are allowed to vary during a cycle are the regenerator matrix temperatures; a technique for speeding up the convergence of these temperatures was used to get a solution in a reasonable amount of computing time. Cylinder and regenerator housing temperatures for conduction calculations can either be inputs or can be calculated from heater and cooler input temperatures.

Losses due to imperfect heat transfer and appendix gap pumping losses are an integral part of the cycle calculations. The appendix gap pumping calculations assume isothermal appendix gaps as in reference 6. A cold appendix gap is included for the sake of generality; however, its volume is very small and its effect is negligible for the P-40 engine. Heat conduction and piston shuttle losses are calculated and are accounted for in the efficiency calculations.

The pressure drop and heat transfer calculations are based on correlations taken from Kays and London (ref. 7). The pressure drop calculations are based on a simplified momentum equation which neglects gas inertia.

Pressure drop calculations are also decoupled from the basic thermodynamic calculations for the working space to neglect pressure wave dynamics. A more rigorous modeling of pressure drop, accounting for pressure wave dynamics, would require a much smaller time step for stable calculations (with the explicit, one iteration per step, numerical integration used in this model).

In the early version of the model reported in reference 1, one pass, consisting of about 25 engine cycles, was made through the cycle calculations. In the model documented here two separate passes, using 25 engine cycles each, are usually made through the cycle calculations. The optional second pass was added to improve the modeling of the effect of pressure drop on engine performance.

Calculated power loss due to pressure drop is about the same whether one or two passes are made. However, in the second pass calculations, the effect of pressure drop on heat transfer to and from the engine is more accurately modeled; the net effect on predicted performance is to increase the basic power (power before pressure drop loss) and efficiency of the engine. More details of the method used to account for the effect of pressure drop on engine performance are discussed in appendix E.

For hydrogen at design P-40 conditions the effect of the second pass is to increase predicted brake power by about 1.2 kW (3.5 percent). For helium at design P-40 conditions a more significant increase, about 1.9 kW (9.7 percent) is found. As indicated above, the significant change is in the basic power (before pressure drop loss) and heat transfer; the power loss due to pressure drop is essentially unchanged. Since the model overpredicted power with one pass, the above changes increase the errors in predicted power. The shape of the revised predicted curve (power as function of speed at constant pressure) does however approximate more closely the shape of the experimental curve.

Real or ideal gas equations of state can be used for pure hydrogen or helium working gas. Only the ideal gas equation of state can be used for a mixture of hydrogen and carbon dioxide. Working gas thermal conductivity, viscosity and specific heats are functions of gas temperature.

Current computing time for the model is about 2.5 minutes for 50 cycles on an IBM 370 or 3 seconds per cycle. This is based on 500 iterations per engine cycle or a time step of $3X10^{-5}$ seconds when the engine frequency is 66.7 Hz (4000 rpm). (1000 iterations per cycle were required to give satisfactory accuracy when trapezoidal integration was used for the work integration as in the model of ref. 1; it was shown there that when the number of iterations per cycle was reduced from 1000 to 200, the error in the prediction of both power and efficiency approached 10 percent; numerical stability was, however, maintained. It was then found that by switching to the more accurate Simpson rule integration, the number of iterations required for good accuracy decreased from 1000 to 500.)

The analytical model upon which the computer program is based is discussed in appendix A. The working gas temperature differential equation used in the model is derived in appendix B. The method used to numerically integrate the decoupled gas temperature differential equation is explained in appendix C. The calculation of expansion and compression space heat transfer coefficients is discussed in appendix D. The simplifications made in the general form of the one dimensional conservation of momentum equation and the decoupled pressure drop calculations are discussed in appendix E. The symbols used in the FORTRAN source programs and the input and output datasets are defined in appendix F. Predictions of the model are compared with P-40 engine data in appendix G.

IV. USERS' MANUAL

A. Overall Simulation Structure

The overall simulation structure is shown in figure 3. The computer model consists of a main program, MAIN, and five subroutines - ROMBC, HEATX, XDEL, CNDCT, and CYCL.

In program MAIN, a data statement specifies the number of heater, regenerator, and cooler control volumes and the number of time steps per cycle. Dimensions for all control volume variables are specified in MAIN; instructions for setting the dimensions are given in comment statements in MAIN. MAIN communicates only with subroutine ROMBC.

ROMBC reads in the basic engine parameters and uses them to calculate control volume geometry; it also reads in engine operating conditions, option switches (indexes), and multiplying factors. ROMBC initializes variables and steps time and crank angle; at each new crank angle it recalculates the variable volumes and calls subroutine HEATX to update the working space heat and mass transfer calculations. ROMBC also integrates to determine work, stores working space variables for plotting, and averages working space variables over the cycle; instantaneous values of working space variable are also written out during each cycle (optional). Regenerator matrix temperature corrections, to speed up convergence, and cooler tube temperature corrections are made in ROMBC at the end of specified cycles. Subroutine CYCL is called at the end of each engine cycle to make summary calculations for the cycle. When predictions are completed for one set of operating conditions and ROMBC does not succeed in reading in a new set of input data, execution returns to MAIN for program termination.

Subroutine HEATX updates pressure, heat transfer, gas temperatures, regenerator matrix temperatures, gas flow rates and sums heat transfers over the cycle for use in energy balance and efficiency calculations. HEATX also calls subroutine XDEL to make a new calculation of engine pressure drop loss and subroutine CNDCT to calculate heat conduction losses.

Subroutine XDEL calculates pressure drop for tube and wire screen friction, tube 45, 90, and 180 degree turns, flow path contractions and expansions; subroutine calling arguments specify the type of pressure drop to be calculated and the flow geometry.

Subroutine CNDCT calculates conduction losses through the cylinder housing, piston and the regenerator housing and also shuttle losses.

Once per cycle, subroutine CYCL calculates the net heat into the engine by adding conduction, shuttle losses, etc., to the heat transferred into the working space over the previous cycle. Mechanical friction loss is calculated. Then net heat out is calculated by adding conduction, shuttle, appendix gap pumping and mechanical friction losses to the heat transferred out of the working space over the previous cycle. CYCL writes out summary results at the end of each engine cycle (optional). After the last engine cycle, CYCL calculates auxiliary losses and brake power and efficiency; it then outputs an overall summary of operating conditions and performance results.

The input data is read into ROMBC. The output data is written from either CYCL or ROMBC. The form of the input and output data will be discussed in the following two sections.

B. Program Setup

Array dimensions for all control volume variables are specified in the main program, MAIN. Several indexes which affect the choice of these dimensions are set in a data statement in MAIN; NH, NR, and NC specify the number of control volumes alotted to the heater, regenerator and cooler, respectively. The index, ISCD, is set equal to 1 to use separate control volumes for the following connecting ducts: expansion space-heater, heater-regenerator, regenerator-cooler, and cooler-compression space. If ISCD = 0 then the connecting duct volumes are lumped with adjacent control volumes. The index, NITPC, specifies the number of time steps per engine cycle (normally = 500).

The engine geometry is defined by reading the engine parameters into subroutine ROMBC. For the test case, the P-40 engine parameters shown in table II were read into ROMBC via NAMELIST/ENGINE/. For convenience, the engine parameters of table II are defined in table III. To set the model up for another engine would require changing these engine parameters, the variable volume equations in subroutine ROMBC, and the mechanical and auxiliary loss equations in subroutine CYCL; the function definition, WINT, used in the work integration in ROMBC, would also need changing to be consistent with new variable volume equations. Also, the calls to the pressure drop subroutine XDEL from subroutine HEATX should be checked to see if the types of pressure drop calculations specified are appropriate for the new engine.

The model option switches and multiplying factors and the engine operating conditions are also defined by reading the appropriate parameters into ROMBC. For the test case these parameters, as shown in table IV, were read in via NAMELIST/STRLNG/ and NAMELIST/INDATA/. The parameters of table IV are defined in tables V and VI.

Multiple runs for a given engine can be made by adding sets of input data (table IV data), sequentially. After a run is complete the program tries to read a new set of input data; if another set of data is not found, the run terminates.

The model options and multiplying factors shown in table V are discussed below:

The parameter REALGS is set equal to 1 to use a real gas equation of state or equal to 0 to use an ideal gas equation. FACT1 and FACT2 are empirical factors used in the procedure for speeding up convergence of regenerator matrix temperatures. The current values, 0.4 and 10, respectively, have yielded satisfactory results for all simulations attempted. The index, NOCYC, specifies the number of engine cycles to be calculated per pass; this is usually set at 25. However, there have been cases when a particular combination of operating conditions and engine parameters required as many as 40 cycles to get satisfactory convergence. (Convergence indicators are the percent errors in the engine and regenerator energy balances. These will be discussed later under Output - Test Case.) NSTRT specifies the cycle number at which the regenerator matrix and cooler temperature convergence procedures are turned on; this is usually set equal to one. The index, NOEND, specifies the cycle number at which the regenerator matrix and cooler temperature convergence procedures are turned off; this index is set at five less than NOCYC. For the last five cycles, the matrix energy equation alone determines regenerator matrix temperatures. This constitutes a check to see if the convergence procedure arrived at a temperature profile consistent with the basic matrix energy equation. (If it did not, then the percent error in the regenerator energy balance will increase during the last five cycles.) The index, MWGAS, = 2 to use hydrogen working gas or = 4 to use helium. RHCFAC, HHCFAC, and CHCFAC are multiplying factors for regenerator, heater and cooler heat transfer coefficients, respectively, for use in sensitivity studies. Set index IPCV = 0 to make a second pass through the calculations or = 1 to eliminate the second pass. The first pass calculations include a correction of engine power and an approximate correction of heat into and out of the engine for the effect of pressure drop; the second pass provides a more accurate calculation of the effect of pressure drop on heat transfer and power. FMULT and FMULTR are overall pressure drop and regenerator pressure drop multiplying factors, respectively. Set index IMIX = 1 to use a mixture of hydrogen and carbon dioxide as the working gas; the mixture is defined by the volume fraction of hydrogen, VH2, which is set next after IMIX, as shown in table V. If IMIX = 1, then REALGS should be set equal to 0 and MWGAS should be set equal to 2. IMIX = 0 for pure hydrogen or helium. Set index IPUMP = 1 to include the piston-cylinder "appendix" gap pumping loss; IPUMP = 0 omits the pumping loss calculation. Set index ICOND = 1 to calculate cylinder and regenerator housing temperatures for conduction calculations from input hot end temperatures (TM(1) and TM(4)) and the coolant inlet temperature (TH2OIN). If ICOND = 0, then the specified input values of cylinder and regenerator housing temperatures are used. The remaining indexes in table V are discussed in the next section, Output Options.

The pressure drop subroutine, XDEL, is set up to calculate pressure drop due to tube friction, wire mesh friction, expansions, contractions, and 45, 90, and 180 degree turns. The desired option is specified by setting the subroutine calling argument, K, to the appropriate value of KTYPE as defined in comment statements in subroutine XDEL (KTYPE, in comment statements = K).

C. Output Options

The last five entries in table V define the output options. Three different sets of output data are available as shown in tables VII to IX. Table VII has been used primarily for debugging purposes and its shortened form, table VIII, has been used very little since the output of table IX was added.

If the index, IOUT (in table V), is set equal to 1, then the value of the index, JIP, determines whether the data of table VII or VIII is output. If JIP = 0, then summary data for each cycle, as shown in table VII is output.

If JIP = 1, the shortened form, table VIII, is output (Symbols and units used in these two tables are defined in the symbols list in appendix F). If IOUT = 0, then neither of these two tables is produced.

At the beginning of table VII, the input parameters and some of the calculated control volume parameters are output in NAMELIST write format. The remaining portion of the table contains summary data for each cycle.

For example, during the first cycle, variables are written out at TIME = 0.0, the beginning of the cycle, and TIME = 0.0150 secs., the end of the cycle. The number of time steps between these variable printouts is specified by the index, IPRINT (table V); thus with 500 time steps per cycle, IPRINT = 500 yields the two lines of printout shown for all except the last 5 cycles (per pass). For the last 5 cycles the number of time steps between variable printouts is changed to IPRINT/25 (= 20 for the test case); variations over the cycle of gas temperatures, pressures, Reynolds Numbers and gas flow rates are shown in these expanded printouts for the last 5 cycles; the last cycle in table VII shows flowrates at intervals of 20 time steps (or 25 printouts per cycle).

Most of the quantities in table VII that are determined by summing or averaging over each time step in a given cycle (such as QIN, heat in per cylinder per cycle, and QOUT, heat out per cylinder per cycle) are also printed out with definitions in table IX. There are some additional working space variable average and maximum values available in the output of table VII (and not in IX) that may be of interest. On the bottom half of the last page of table VII are average gas and metal temperatures (TGACYC, TMCYC), average and maximum heat transfer coefficients (HACYC, HMX), and, average and maximum heat fluxes (QOAAVG, QOAMX); these values are shown for expansion and compression spaces, connecting ducts, and the hot and cold end control volumes for each heat exchanger. Expansion space values are at the extreme left and compression space values are at the extreme right. Near the bottom of the page, brake power per cylinder, AUXPWR, and brake efficiency, AUXEFF, are found; these can be checked against the corresponding values in table IX for consistency.

The index, ITMPS (table V), can be set equal to 1 to print variable temperatures at each time step for debugging purposes. The index, MAPLOT, = 1 to store cycle variables for plotting or = 0 to skip the storage procedure; the particular variables to be stored are specified in the FORTRAN coding of subroutine ROMBC.

Table IX, the Final Summary Printout, is written out after the final cycle for each set of input data; no provision is made for switching off this output. Table IX includes a summary of the engine operating conditions and predicted performance. The predicted performance includes an engine energy balance. For example the brake power plus total heat rate from the engine should equal the heat rate to the engine for a perfect energy balance. The values printed out in table IX show that the energy balance error for the test case, on a 4 cylinder basis, is:

$$\left(\frac{\text{BRAKE POWER} + \text{TOTAL HEAT RATE FROM ENGINE}}{\text{TOTAL HEAT RATE TO ENGINE}} - 1 \right) \times 100 = \left(\frac{37.239\ \text{kw} + 102.100\ \text{kW}}{138.931\ \text{kW}} - 1 \right)$$

$$\times\ 100 = 0.294\ \text{percent}$$

Brake and indicated engine efficiencies are also shown. Table IX also shows heat flows into and out of the engine separated into various parts. Regenerator heat flows, per cent error in regenerator energy balance and two measures of regenerator effectiveness are shown; the two measures of regenerator effectiveness are defined in the table (The two most important criteria in determing whether the simulation has converged satisfactorily to a solution are the percent error in the engine energy balance and the percent error in the regenerator energy balance). Overall pressure drop is shown separated into parts by component. Maximum and minimum pressures and pressure ratios are shown for expansion and compression spaces.

D. Program Execution

Table X shows which Read/Write FORTRAN statement unit numbers, in subroutines ROMBC and CYCL, were linked with the test case input and output data. For example, item 1 in table X indicates that a read statement in subroutine ROMBC used unit number 4 to read in the input data of table II.

The P-40 simulation test case was initiated by using system commands to:

1. Link the READ unit #'s with the appropriate sets of input data as shown in table X.

2. Link the WRITE unit #'s with the desired locations for the tables of output data.

3. Execute the main program, MAIN.

V. OUTPUT--TEST CASE

A sample run was made using the input data shown in tables II and IV. The engine parameters specified in table II, the variable volume equations in subroutine ROMBC, and the mechanical and auxiliary loss equations in subroutine CYCL set the model up to simulate the United Stirling P-40 engine. The operating conditions specified in table IV correspond to a NASA Lewis P-40 experimental run which approximated the design operating conditions of the engine (15 MPa (2175 lbf/in^2), 66.78 Hz (4000 rpm)). The effective outside heater tube temperature was estimated to be 930 K (1672° R); the cooling water inlet temperature was 323 K (580° R), and the cooling water flow rate was 0.860 liter/sec (13.6 gal/min).

The previously discussed tables of output data (VII to IX) were generated using the above test case operating conditions. Table IX shows that brake power and efficiency predicted for the P-40 at the specified operating conditions are 37.2 kW and 0.268, respectively. This efficiency does not account for external heat system (combustor) losses. Predicted heat flows, pressure drop losses and pressure ratios are also shown in table IX.

The index, MAPLOT, was set equal to 1 (table IV) for the test case to store the cycle variables for plotting. A separate plotting program (not documented in this report) using the IBM 370 graphics package was used to read in the stored data and make plots. The results are shown in figures 4 to 9. Expansion and compression space pressures are shown as a function of crank angle in figure 4. Expansion and compression space volumes are shown in figure 5. Expansion and compression space gas temperatures are shown in figures 6(a) and (b), respectively. They are also shown plotted to the same scale in figure 6(c). Gas flow rates out of the expansion space and into the compression space are shown in figure 7; flow is assumed positive from the expansion space toward the compression space (flow rates are also calculated at each interface between control volumes). Overall engine pressure drop (expansion space pressure minus compression space pressure) is shown in figure 8. P-V diagrams for expansion and compression space are shown superimposed in figure 9.

VI. CONCLUDING REMARKS

Testing of the United Stirling P-40 engine at NASA-Lewis has provided engine performance data for comparison with the predictions of this model. A comparison of a small portion of this data with predictions of this model is discussed in appendix G.

There are several possibly significant losses which have not been included in the model and so have not been evaluated for the P-40 engine. Papers by Kangpil Lee (refs. 8 and 9) suggest that cyclic heat transfer or hysteresis loss due to heat exchange between working gas and cylinder walls may be significant for engines as small as the GPU-3. Also, no attempt has been made to evaluate losses due to non-uniform flow distribution or regenerator matrix "by-pass flow" (that is, flow near the regenerator housing that does not exchange heat effectively with the matrix and thus degrades the effectiveness of the regenerator)

The model's qualitative ability to predict variations in the state of the working gas over the cycle and to predict performance trends has been useful in helping to understand operation of the engine, to plan the experimental program, and to study sensitivity to various engine and working gas parameters. The model was recently used to generate a performance map for a 37 kW (50 hp) scaled down version of a United Stirling 67 kW (90 hp) engine design. The performance map was then input to a vehicle driving cycle code which was used to predict the fuel economy of a 37 kW Stirling engine powered vehicle.

Predictions made with helium working gas tend to result in regenerator effectivenesses that appear too high unless an adjustment is made in the slope of the temperature variation across the regenerator control volumes. A typical adjustment made for helium gas is to multiply the quantity, DTGASL, in subroutine HEATX by 0.95 (the model is set up to make this adjustment automatically when helium working gas is specified).

With relatively minor modification the model should be able to simulate Stirling cycle refrigerators or heat pumps. For the refrigerator application it would be necessary to define the working gas properties over a lower range of operating temperatures.

VII. APPENDIXES

APPENDIX A: Analytical Model

A rigorous simulation of the gas dynamics in the working space of a Stirling engine would require solution of a set of partial differential equations. The simulation problem can be simplified by assuming the flow is essentially one-dimensional and dividing the working space into control volumes; a set of ordinary differential equations is then solved for each of the control volumes; this is the approach is used here.

Each of the control volumes shown in figure 2 is a special case of the generalized control volume shown in figure 10. The generalized control volume includes mass flow across two surfaces, heat transfer across one surface, and work interchange between gas and piston. Only the expansion and compression space control volumes are variable.

The basic equations used to model the thermodynamics of the gas in each control volume are conservation of energy, mass, momentum and an equation of state. These equations are used to determine temperature, pressure and mass distributions within the working space at a particular time.

The energy, mass and state equations, as written for the generalized control volume shown in figure 10, are as follows, where three formulations of the equations of state are shown:

Conservation of energy (for negligible change in kinetic energy across the control volume):

$$\frac{d}{dt}(MC_vT) = hA(T_w - T) + (C_{p_i}W_iT_i - C_{p_o}W_oT_o) - P\frac{dV}{dt} \qquad (1)$$

Rate of change of internal energy of control volume	Rate of heat transfer across boundary of control volume	Rate of enthalpy flow across boundary of control volume	Rate of work done by gas in control volume

Conservation of mass:

$$\frac{dM}{dt} = W_i - W_o \qquad (2)$$

Equation of state:

$PV = MRT$ for ideal gas

$PV = MR[T + 0.02358\ P]$ for hydrogen-real gas (3)

$PV = MR[T + 0.01613\ P]$ for helium-real gas

where

A	heat-transfer area of control volume
C_p, C_v	heat capacities at constant pressure and volume
h	heat-transfer coefficient
M	mass of gas in volume
P	pressure
R	gas constant
T	bulk or average temperature of gas in volume
T_i, T_o	temperatures of gas flowing across surfaces i and o, respectively (in fig. 10)
T_w	temperature of metal wall adjacent to heat-transfer area, A
t	time
V	volume
W_i, W_o	flow rate across surfaces i and o, respectively

(The real-gas equations of state were developed from data in ref. 10)

Several assumptions are inherent in the use of these equations:

(1) Flow is one dimensional.

(2) Heat conduction through the gas and the regenerator matrix along the flow axis is neglected. The thermal conductivity of the regenerator matrix is assumed to be infinite in calculating the overall gas-to-matrix heat-transfer coefficient.

(3) Kinetic energy can be neglected in the energy equation.

(4) The time derivative term in the momentum equation is neglected (see appendix E).

In appendix B it is shown that equations (1) and (2) and the ideal-gas equation of state can be used to derive the following differential equation:

$$MC_p \frac{dT}{dt} = hA(T_w - T) + (W_o - W_i)C_pT + (C_{p_i}W_iT_i - C_{p_o}W_oT_o) + V\frac{dP}{dt} - MT\frac{dC_p}{dt} \quad (4)$$

The same result is obtained if either of the real-gas equations of state are used in the derivation. This equation says that the bulk or average gas temperature of a control volume is a function of the following four processes:

(1) Heat transfer across the boundary from the wall

(2) Gas flow across the boundary

(3) Changes in pressure level

(4) Changes in working gas specific heat

Equation (4) can be solved for the temperature derivative to get:

$$\frac{dT}{dt} = \frac{hA}{MC_p}(T_w - T) + \frac{(W_o - W_i)}{M} T + \frac{\left(C_{p_i} W_i T_i - C_{p_o} W_o T_o\right)}{MC_p} + \frac{V}{MC_p}\frac{dP}{dt} - \frac{T}{C_p}\frac{dC_p}{dt} \qquad (5)$$

The approach used in numerically integrating equation (5) (suggested by Jefferies, ref. 1) was to decouple the four processes that contribute to the temperature change and solve for the temperature change due to each process separately. This approach allows a trade-off between computing time and accuracy of solution with little concern for numerical instabilities. The approach is suggested by representation of equation (5) in the following form:

$$\left.\frac{dT}{dt}\right|_{\text{total}} = \left.\frac{dT}{dt}\right|_{\substack{\text{due to}\\ \text{heat transfer}}} + \left.\frac{dT}{dt}\right|_{\substack{\text{due to}\\ \text{mixing}}} + \left.\frac{dT}{dt}\right|_{\substack{\text{due to}\\ \text{pressure}\\ \text{change}}} + \left.\frac{dT}{dt}\right|_{\substack{\text{due to}\\ \text{change in}\\ \text{specific}\\ \text{heat}}}$$

where

$$\left.\frac{dT}{dt}\right|_{\substack{\text{due to change}\\ \text{in specific heat}}} = -\frac{T}{C_p}\frac{dC_p}{dt} \qquad (5a)$$

$$\left.\frac{dT}{dt}\right|_{\substack{\text{due to change}\\ \text{in pressure}}} = \frac{V}{MC_p}\frac{dP}{dt} \qquad (5b)$$

$$\left.\frac{dT}{dt}\right|_{\substack{\text{due to}\\ \text{mixing}}} = \frac{(W_o - W_i)}{M} T + \frac{\left(C_{p_i} W_i T_i - C_{p_o} W_o T_o\right)}{MC_p} \qquad (5c)$$

$$\left.\frac{dT}{dt}\right|_{\substack{\text{due to}\\ \text{heat transfer}}} = \frac{hA}{MC_p}(T_w - T) \qquad (5d)$$

In appendix C it is shown that equations (5a), (b), and (d) can be integrated in closed form and that equation (5c) can be numerically integrated. When the results of appendix C are modified slightly to show just how they are used in the model, the resulting expressions are:

$$T_s^{t+\Delta t} = T^t \frac{C_p^t}{C_p^{t+\Delta t}} \qquad (5a')$$

$$T_{sp}^{t+\Delta t} = T_s^{t+\Delta t} \left(\frac{p^{t+\Delta t}F^{t+\Delta t}}{p^tF^t}\right)^{\frac{R}{C_p^{t+\Delta t}}} \qquad (5b')$$

$$T_{spm}^{t+\Delta t} = \frac{M^t}{M^{t+\Delta t}} T_{sp}^{t+\Delta t} + \frac{\left(C_{p_i}^{t+\Delta t}W_i^{t+\Delta t}T_i^{t+\Delta t} - C_{p_o}^{t+\Delta t}W_o^{t+\Delta t}T_o^{t+\Delta t}\right)}{M^{t+\Delta t}C_p^{t+\Delta t}} \qquad (5c')$$

$$T^{t+\Delta t} = T_{spm}^{t+\Delta t} + \left(T_w^t - T_{spm}^{t+\Delta t}\right)\left[1 - e^{-\left(h^{t+\Delta t}A/M^{t+\Delta t}C_p^{T+\Delta t}\right)\Delta t}\right] \qquad (5d')$$

where the superscripts t and $t+\Delta t$ denote values of the variables at times t and $t+\Delta t$. The subscript S denotes the value of the temperature after it has been updated for the effect of change in the specific heat. The subscript SP denotes the value of the temperature after it has been updated for the effect of change in specific heat and pressure. The subscript SPM denotes the value of the temperature after it has been updated for the effects of change in specific heat, pressure and mixing. No subscript (as on the left side of eq. (5d')) denotes the value of the temperature after it has been updated for all four effects-change in specific heat, pressure, mixing, and heat transfer to or from the metal.

Discussion of Equations in Order of Calculation Procedure

The equations considered so far have been derived and discussed with reference to the generalized control volume of figure 10. In the computer model these equations are applied to each of the control volumes shown in figure 2. Thus temperatures, masses, heat-transfer coefficients, flow rates, etc., are all subscripted with an index for the non-isothermal control volumes. The index varies from 1 to NCV for variables that are averages for the control volumes and from 1 to NCV-1 for variables defined at the interfaces between control volumes (as shown in fig. 2). The equations discussed in this section include these indexes. The discussion of the equations follows the steps shown in the outline of calculation procedure in figure 11.

Update Time and Crank Angle, ROMBC (Step 1, Fig. 11):

Time is an independent variable input to the computer model. The assumption of constant frequency means that both crank angle and time are updated by fixed steps at the beginning of each iteration. There are NITPC (= 500, usually) fixed time and crank angle steps per engine cycle.

Compression and Expansion Space Volumes, ROMBC (Step 2, Fig. 11):

Equations for expansion and compression space volumes as a function of crankshaft angle are as follows:

$$V_e = A_p \left[r(1. - \cos \alpha) + L\left(1. - \sqrt{1. - \left(\frac{r}{L} \sin \alpha\right)^2}\right)\right] + V_{e,\ \text{clearance}} \quad (6)$$

$$V_c = A_{pr} \left[r\left(1. - \cos\left(\alpha + \frac{\pi}{2}\right)\right) - L\left(1. - \sqrt{1. - \left(\frac{r}{L} \sin\left(\alpha + \frac{\pi}{2}\right)\right)^2}\right)\right] + V_{c\ \text{clearance}}, \quad (7)$$

where V_e, clearance includes the hot appendix gap volume and V_c, clearance includes the cold appendix gap volume - only if the appendix gap pumping losses are not calculated (that is, only if the index, IPUMP = 0)

where

V_e	expansion-space volume
V_c	compression-space volume
A_p	piston cross-sectional area
A_{pr}	piston minus piston rod cross-sectional area
r	crank radius
L	piston rod length
α	crank angle

Thermal Conductivity and Viscosity Equations (Step 3):

The equations used in subroutine ROMBC to calculate gas thermal conductivity and viscosity (for hydrogen, helium and carbon dioxide) assume both quantities vary linearly with temperature. The equations are derived from data in reference 11. The mixture equations used to determine the conductivity and viscosity for a mixture of hydrogen and carbon dioxide are based on information in references 12 and 13.

Pressure (Step 4):

The pressure P is calculated by

$$P^{t+\Delta t} = R \frac{\sum_{I=1}^{NCV} M_I^t T_I^t}{\sum_{I=1}^{NCV} V_I^{t+\Delta t} F_I^{t+\Delta t}} \quad \text{if IPUMP} = 0$$

$$= R \frac{M^t_{hgp} T_{hgp} + \sum_{I=1}^{NCV} (M^t_I T^t_I) + M^t_{cgp} T_{cgp}}{V_{hgp} F_1^{t+\Delta t} + \sum_{I=1}^{NCV} (V_I^{t+\Delta t} F_I^{t+\Delta t}) + V_{cgp} F_{NCV}^{t+\Delta t}} \quad \text{if IPUMP} = 1 \tag{8}$$

where

P	pressure at center of regenerator
R	gas constant
M	control volume mass
T	control volume average temperature
V	control volume
F	ratio of pressure in control volume to pressure at center of regenerator
I	index denoting which of control volumes 1 through NCV is under consideration
hgp	subscript denoting isothermal hot gap control volume
cgp	subscript denoting isothermal cold gap control volume

Equations (8) are obtained by first writing the ideal-gas equation for the Ith control volume

$$P_I V_I = (F_I P) V_I = M_I R T_I$$

where

P_I pressure in Ith control volume

then summing over each of the control volumes under consideration and solving for P, the pressure at the center of the regenerator.

Equations (8) indicate that if appendix gap pumping losses are included in the model (by setting IPUMP = 1), then the summation is over each of the 1 through NCV plus the two isothermal appendix gap control volumes. If appendix gap pumping losses are not included (IPUMP = 0) then the appendix gap volumes are lumped with expansion and compression space clearance volumes and the summation is only over the 1 through NCV control volumes. The appendix gap pumping loss model used is based on the one in reference 6.

If the real-gas equation of state for hydrogen is used and the same procedure is followed, the result is:

$$P^{t+\Delta t} = R \frac{\sum_{I=1}^{NCV} M_I^t T_I^t}{\sum_{I=1}^{NCV} F_I^{t+\Delta t} V_I^{t+\Delta t} - 0.02358\ R \sum_{I=1}^{NCV} \left(F_I^{t+\Delta t} M_I^t\right)} \quad \text{if IPUMP = 0}$$

$$= R \frac{M_{hgp}^t T_{hgp} + \sum_{I=1}^{NCV} (M_I^t T_I^t) + M_{cgp}^t T_{cgp}}{\left[\left(F_1^{t+\Delta t} V_{hgp} + \sum_{I=1}^{NCV} \left(F_I^{t+\Delta t} V_I^{t+\Delta t}\right) + F_{NCV}^{t+\Delta t} V_{cgp}\right) - 0.02358\ R \left(F_1^{t+\Delta t} M_{hgp}^t + \sum_{I=1}^{NCV} \left(F_I^{t+\Delta t} M_I^t\right) + F_{NCV}^{t+\Delta t} M_{cgp}^t\right)\right]} \quad \text{if IPUMP = 1} \tag{9}$$

Equations (8) and (9) are both included in the model. Also an equivalent real-gas equation for helium is included. An index, REALGS (table IV), specifies whether a real or ideal equation is to be used.

The variable, F, represents an array of pressure ratios with different values for each control volume at each time step over an engine cycle. F is used above to evaluate the effect of the decoupled pressure drop calculations on pressure level at the center of the regenerator. F is defined as follows:

During the first pass through the calculations (NOCYC cycles), each element of F = 1. At the end of the first pass, pressure drop information for each control volume at each time step is stored in F; each element represents the ratio of pressure at a particular control volume and increment of time to pressure at the center of the regenerator. Thus the array appears as:

$$F_{i,k} = \begin{array}{cc} \begin{bmatrix} F_{1,1} & F_{1,2} \cdots\cdots & F_{1,NRC-1} & 1 & F_{1,NRC+1} \cdots & F_{1,NCV} \\ F_{2,1} & F_{2,2} \cdots\cdots & F_{2,NCR-1} & 1 & F_{2,NRC+1} \cdots & F_{2,NCV} \\ \vdots & & & & & \\ \vdots & & & & & \\ F_{NITPC,1} & F_{NITPC,2} \cdots\cdots & F_{NITPC,NRC-1} & 1 & F_{NITPC,NRC+1} \cdots & F_{NITPC,NCV} \end{bmatrix} & \begin{array}{c} \text{NITPC} \\ \text{ROWS} \\ \text{(time} \\ \text{increases)} \end{array} \downarrow \\ \text{——— NCV COLUMNS} \longrightarrow & \end{array}$$

where

NCV = 17

NRC = 9

time steps per engine cycle, NITPC = 500 for the sample runs.

This array of pressure drop information is used in the second pass (NOCYC additional cycles).

The second pass, using the array F, was incorporated to get a more accurate evaluation of the effect of the decoupled pressure drop on the thermodynamic calculations. The method is discussed in more detail in appendix E.

Update Gas Specific Heats (Step 5):

The equations used to calculate gas specific heats in subroutine HEATX assume a quadratic variation with temperature (except for helium whose specific heat is essentially constant over the temperature range of interest). The equations are derived from data in reference 11.

Update Temperatures for Effect of Change in Specific Heat (Step 6):

Introducing the control volume index, I, into equation (5a'), the form of the equation used to correct gas temperatures for the effect of changes in specific heat is:

$$T_{I,s}^{t+\Delta t} = T_I^t \frac{C_{p_I}^t}{C_{p_I}^{t+\Delta t}} \tag{10}$$

Update Temperatures for Effect of Change in Pressure (Step 7):

$$T_{I,sp}^{t+\Delta t} = T_{I,s}^t \left(\frac{P^{t+\Delta t} F_I^{t+\Delta t}}{P^t F_I^t} \right)^{\frac{R}{C_{p_I}^{t+\Delta t}}} \tag{11}$$

This equation is commonly used to relate temperature and pressure for an adiabatic fixed-mass process.

Mass Distribution (Step 8):

On the first pass through the calculations the mass distribution is determined by assuming that the mass redistributes itself in accordance with the new volumes and temperatures in such a way that pressure is uniform throughout the working space. The pressure, P, throughout the working space is derived from the perfect-gas law as follows:

The perfect-gas law for the Ith control volume can be written

$$M_I = \frac{F_I P V_I}{R T_I}$$

Summing over the NCV control volumes (and the two isothermal appendix gaps control volumes if IPUMP = 1)

$$M_{TOTAL} = \sum_{I=1}^{NCV} M_I = \frac{P}{R} \sum_{I=1}^{NCV} \frac{F_I V_I}{T_I} \qquad \text{if IPUMP} = 0$$

$$= M_{hgp} + \sum_{I=1}^{NCV} (M_I) + M_{cgp} = \frac{P}{R}\left[\frac{F_1 V_{hgp}}{T_{hgp}} + \sum_{I=1}^{NCV}\left(\frac{F_I V_I}{T_I}\right) + \frac{F_{NCV} V_{cgp}}{T_{cgp}}\right]$$

if IPUMP = 1

Solving for P/R for the case, IPUMP = 0, gives

$$\frac{P}{R} = \frac{M_{total}}{\sum_{I=1}^{NCV} \frac{F_I V_I}{T_I}} \qquad \text{IPUMP} = 0$$

Now substituting for P/R into the perfect-gas equation for the Ith control volume gives

$$M_I = \frac{M_{total}}{\sum_{I=1}^{NCV} \frac{F_I V_I}{T_I}} \frac{F_I V_I}{T_I} \qquad \text{IPUMP} = 0$$

The form of this equation used in the model to calculate the working gas mass in each of the NCV control volumes is:

$$M_I^{t+\Delta t} = M_{total} \frac{\dfrac{F_I^{t+\Delta t} V_I^{t+\Delta t}}{T_{I,sp}^{t+\Delta t}}}{\sum_{I=1}^{NCV} \left[\dfrac{F_I^{t+\Delta t} V_I^{t+\Delta t}}{T_{I,sp}^{t+\Delta t}}\right]} \quad IPUMP = 0 \tag{12}$$

(where $T_{I,sp}^{t+\Delta t}$ represents T updated for changes in specific heat and pressure

but not for mixing and heat transfer).

The preceding equation calculates the new mass distribution for the case of a perfect gas. The following equation, which can be derived in the same manner, is used to approximate the real properties of hydrogen for the case of no appendix gap pumping loss:

$$M_I^{t+\Delta t} = M_{total} \frac{\dfrac{F_I^{t+\Delta t} V_I^{t+\Delta t}}{(T_{I,sp}^{t+\Delta t} + 0.02358\ P^{t+\Delta t})}}{\sum_{I=1}^{NCV} \left[\dfrac{F_I^{t+\Delta t} V_I^{t+\Delta t}}{T_{I,sp}^{t+\Delta t} + 0.02358\ F_I^{t+\Delta t} P^{t+\Delta t}}\right]} \tag{13}$$

A similar equation that approximates the real properties of helium is included in the model.

When appendix gap pumping losses are included (IPUMP = 1) then the summations used in deriving the equivalents of equations (12) and (13) are over the 1 through NCV plus the two isothermal appendix gap control volumes.

<u>Flow Rates (Step 9)</u>:

Once the new mass distribution is known, the new flow rates are calculated from the old and new mass distributions according to

$$W_o = \frac{M_o^t - M_o^{t+\Delta t}}{\Delta t} \quad \text{if IPUMP} = 1$$

and (14)

$$W_I = \frac{M_I^t - M_I^{t+\Delta t}}{\Delta t} + W_{I-1} \qquad \begin{array}{l} I = 1,NCV \text{ if IPUMP} = 1 \\ \text{or } I = 1,NCV-1 \text{ if IPUMP} = 0 \end{array}$$

where

M_0 = mass in hot appendix gap if IPUMP = 1 (not used if IPUMP = 0)

W_0 = FHGP, flow from hot gap to expansion space, if IPUMP = 1 (not used if IPUMP = 0

W_{NCV} = FCGP, flow to cold gap from compression space, if IPUMP = 1 (not used if IPUMP = 0)

W_I = is the flow rate at the Ith interface between control volumes.

Update Temperatures in Each Control Volume for Effect of Gas Flow Between Control Volumes (Step 10):

The following equation (modification of eq. (5c')) was used to update temperature for the mixing effect following gas flow between control volumes:

$$T_I^{t+\Delta t} = \frac{M_I^t}{M_I^{t+\Delta t}} T_{I,sp}^{t+\Delta t} + \frac{\left(C_{p_{I-1}}^{t+\Delta t} W_{I-1}^{t+\Delta t} \theta_{I-1}^{t+\Delta t} - C_{p_I}^{t+\Delta t} W_I^{t+\Delta t} \theta_I^{t+\Delta t}\right)}{M_I^{t+\Delta t} C_p^{t+\Delta t}} \tag{15}$$

$I = 1,NCV$ (IPUMP = 1)

(where the temperature $T_{I,sp}^{t+\Delta t}$ has already been updated for specific heat change and pressure change).

The temperature of the fluid flowing across the interface has been given a new variable name, θ, to better distinguish it from the average control volume temperature, T, and to keep the subscripts as simple as possible. The procedure used to update the temperature, θ, for each interface is now defined.

The temperature of the fluid flowing across a control volume boundary is just the bulk temperature of the control volume from which the fluid came - for flow from the expansion space, heater, cooler, or compression space control volumes or hot and cold appendix gap volumes. This is a reasonable assumption for these volumes since the actual temperature gradient across each is expected to be relatively small. In a five-control-volume regenerator, however, the temperature gradient is not small. One option would be to increase the number of control volumes in the regenerator. However, to save computing time, an alternative approach was used. It was assumed that a temperature gradient existed across each volume in the regenerator. The magnitude of the gradient was assumed to be equal to the corresponding regenerator metal gradient.

A schematic of a regenerator control volume is shown in figure 12(a). Flow across both interfaces is, for now, assumed to be in the direction shown (which is defined to be the positive flow direction). The cross-hatched area represents the portion of the fluid that will flow across interface I during the time step, Δt. The assumed temperature profile of the control volume is characterized in figure 12(b). The vertical dashed line in figure 12(b) defines the temperature at the left boundary of the fluid that will flow across interface I during Δt. If T_I is defined as the average temperature of control volume I and ΔT_I equals one-half the change in temperature across the control volume, then $T_I - \Delta T_I$ is the temperature of the fluid at interface I and

$$T_I - \Delta T_I + \frac{W_I \Delta t}{M_I} 2 \; \Delta t_I$$

is the temperature of fluid at the vertical dashed line. (figure 2 shows the numbering methods used for the control volumes and the interfaces between control volumes).

The temperature of the fluid that flows across an interface during Δt is assumed to be equal to the average temperature of that fluid before it crosses the interface. The average temperature of the fluid in the cross-hatched area of figure 12(a) is then

$$\frac{1}{2}\left[\left(T_I - \Delta T_I + \frac{W_I \Delta t}{M_I} 2 \; \Delta T_I\right) + (T_I - \Delta T_I)\right] = T_I - \Delta T_I + \frac{W_I \Delta t}{M_I} \Delta T_I$$

Therefore, for the flow directions shown in figure 12(a), the updated temperatures of the fluid that crosses the interfaces during Δt are

$$\theta_I^{t+\Delta t} = T_{I,SP}^{t+\Delta t} - \Delta T_I + \frac{W_I^{t+\Delta t} \Delta t}{M_I^t} \Delta T_I, \quad W_I^{t+\Delta t} > 0$$

$$\theta_{I-1}^{t+\Delta t} = T_{I-1,SP}^{t+\Delta t} - \Delta T_{I-1} + \frac{W_{I-1}^{t+\Delta t} \Delta t}{M_{I-1}^t} \Delta T_{I-1}, \quad W_{I-1}^{t+\Delta t} > 0 \tag{16}$$

If the flow direction is reversed at both interfaces, then

$$\theta_I^{t+\Delta t} = T_{I+1}^{t+\Delta t} + \Delta T_{I+1} + \frac{W_I^{t+\Delta t}\Delta t}{M_{I+1}^t}\Delta T_{I+1}, \quad W_I^{t+\Delta t} < 0$$

$$\theta_{I-1}^{t+\Delta t} = T_I^{t+\Delta t} + \Delta T_I + \frac{W_{I-1}^{t+\Delta t}\Delta t}{M_I^t}\Delta T_I, \quad W_{I-1}^{t+\Delta t} > 0 \tag{17}$$

Heat Transfer Coefficients (Step 11):

The heat transfer coefficient calculations for heater and cooler are derived from figure 7-1, page 123 of reference 7; heat transfer coefficient calculations for the regenerator are derived from figure 7-9, page 130 of the same reference. The assumption used in calculating heat transfer coefficients for the expansion and compression spaces are discussed in appendix D.

Update Temperature in Each Gas Control Volume for Effect of Heat Transfer Between Gas and Metal (and Determine Heat Transfer Between Gas and Metal) (Step 12):

This temperature update for control volumes 1 through NCV is accomplished by using the following equation (a modification of equation (5d')):

$$T_I^{t+\Delta t} = T_{I,SPM}^{t+\Delta t}\left(T_{W,I}^{t} - T_{I,SPM}^{t+\Delta t}\right)\left[1 - e^{-\left(\frac{h_I^{t+\Delta t}A_I}{M_I^{t+\Delta t}C_{p_I}^{t+\Delta t}}\right)\Delta t}\right] \qquad I=1,NCV$$

where $T_{W,I}$ is the wall temperature of the Ith control volume. Note that, no matter how large the heat-transfer coefficient, the gas temperature cannot change more than the ΔT between the wall and the gas. Thus this calculation cannot cause the solution to become unstable, but it can lead to significant inaccuracies if the time increment, Δt is made too large.

The heat transferred between gas and metal is then calculated from:

$$Q_I^{t+\Delta t} = -\left(T_I^{t+\Delta t} - T_{I,SPM}^{t+\Delta t}\right)M_I^{t+\Delta t}C_{p_I}^{t+\Delta t} \qquad I=1,NCV \tag{18}$$

so that heat transfer from gas to metal is defined to be positive.

The appendix gap control volumes are assumed to be isothermal. Three steps are used to calculate the heat transfer between the cylinder wall and the appendix gap working gas that would be required to maintain constant gap temperature.

For the hot appendix gap:

1. The change that would occur in appendix gap temperature due to pressure change if there were no heat exchange with the cylinder wall is:

$$\Delta T_{hgp} = T_{hgp}\left(\frac{P^{t+\Delta t}F_1^{t+\Delta t}}{P^t F_1^t}\right)^{\frac{R}{C_{p_{hgp}}}} - T_{hgp}$$

F_1 is used since there is assumed to be no pressure drop between the hot gap and the expansion space.

2. The net change that would occur in appendix gap temperature due to pressure change and mixing, if there were no heat exchange, is calculated by adding an additional "mixing" term to the above expression when there is flow from the expansion space to the appendix gap. That is:

$$\Delta T_{hgp} = \Delta T_{hgp} + \frac{\left[\left(M_{hgp}^{t} - M_{hgp}^{t+\Delta t}\right)C_{p_{hgp}} T_{hgp} - W_o C_{p_{hgpI}}^{t+\Delta t} T_{hgpI}^{t+\Delta t}\Delta t\right]}{M_{hgp}^{t+\Delta t} C_{p_{hgp}}}$$

where

hgp is a subscript denoting quantities within the hot gap control volume

hgp_I is a subscript denoting variable values at the flow interface between the expansion space and the appendix gap.

3. The rate of heat exchange with the cylinder wall required to maintain an isothermal appendix gap is then calculated to be:

$$Q_{hgp} = \frac{\Delta T_{hgp} M_{hgp}^{t+\Delta t} C_{p_{hgp}}}{\Delta t}$$

A similar set of calculations is made for the cold appendix gap.

Regenerator Metal Temperature (Step 13):

The equation used to update the metal temperatures in the regenerator control volumes is

$$M_I C \frac{dT_{w,I}}{dt} = Q_I \qquad I=NR1,NRL \tag{19}$$

where Q_I is the rate of heat transfer between gas and metal. This is integrated numerically by setting

$$T_{w,I}^{t+\Delta t} = T_{w,I}^{t} + \frac{Q_I^{t+\Delta t}}{M_I C} \Delta t \tag{20}$$

where

M_I mass of metal in Ith volume
C thermal capacitance of metal
Δt time increment

For most regenerators the thermal capacitance of the metal is so much larger than the thermal capacitance of the adjacent gas volume that an excessive number of engine cycles (from the point of view of computing time) are required for the metal temperatures to reach steady state. Therefore, it is necessary to apply a correction to the metal temperatures after each cycle to speed up convergence. The method used is discussed in a later section.

Pressure-drop Calculations (Step 14):

Since the pressure-drop calculations have been decoupled from the heat and mass transfer calculations, pressure drop need not be re-calculated over every cycle. Pressure drops are re-calculated only every third cycle. Thus the indicated work calculation is corrected using the most recently calculated loss.

A general form of the conservation of momentum equation for one-dimensional flow is:

$$\frac{\partial}{\partial t}(\rho v) = \frac{\partial}{\partial x}(\rho v^2) - \frac{f}{d_h}\frac{1}{2}\rho v^2 - \frac{\partial P}{\partial x} \tag{21}$$

Rate of accumulation of momentum per unit volume	Rate of momentum gain by convection per unit volume	Rate of momentum gain by viscous transport per unit volume	Rate of momentum gain due to pressure force per unit volume

where

ρ	density
v	velocity of flow
f	friction factor
D_h	hydraulic diameter
P	pressure
t	time
x	distance

In appendix E it is shown that by combining the continuity and momentum equations and then neglecting the time derivative term in the resulting equation, the following equation results:

$$v dv + \frac{f v^2}{2D_h} dx + \frac{dP}{\rho} = 0 \tag{22}$$

This equation can be integrated over a length L for the special cases of adiabatic or isothermal flow processes (the two extremes). When the resulting adiabatic and isothermal expressions were applied to the P-40 heat exchangers (by setting index, K, appropriately in the call to subroutine XDEL from subroutine HEATX for heat exchanger pressure drop calculations), the contribution of the vdv term was negligible for the two extremes. By neglecting the vdv term, the expression for pressure drop is reduced to

$$\frac{f}{2} \frac{v^2}{D_h} dx + \frac{dP}{\rho} = 0 \tag{23}$$

or applying the differential equation (23) over a finite length L

$$\Delta P = \frac{f}{D_h} \frac{1}{2} \rho v^2 L \tag{24}$$

where ΔP is the pressure drop over length L (using the adiabatic or isothermal forms of the pressure drop equation with the vdv term retained requires an iterative solution procedure which increases computing time by about 20 percent).

A modification of this equation can also be used to account for the effect of expansions and contractions in flow area. The form of the modified equation is:

$$\Delta P = K \frac{1}{2} \rho v^2 \tag{25}$$

It is applied at each area change in the flowpath between the expansion and compression spaces. At a particular point where an area change occurs, K is a function of the two areas and the direction of flow (since an expansion for one flow direction is a contraction when the flow reverses). The term, K ,is calculated in accordance with the procedure given in references 14 and 15. Values of K are also specified to account for pressure drop due to tube bends.

The types of pressure drop calculations that can be made in subroutine XDEL are specified by the calling argument, K, and are defined in comment statements in the subroutine (KTYPE, in comment statements = K).

For the heater and cooler control volumes the friction factor, f, is determined from equations based on figure 7-1, page 123 of reference 7. The friction factor for the regenerator is derived from figure 6.3-1, page 6-35 of reference 16.

With the pressure level, P, known (assumed to be the pressure at the center of the regenerator) and the ΔP's across each of the control volumes calculated, the pressures needed in the work calculations, P_e and P_c , can be calculated as follows:

$$P_e = \sum_{I=2}^{NRC-1} \Delta P_I + \frac{\Delta P_{NRC}}{2} + P$$

$$P_c = P - \frac{\Delta P_{NRC}}{2} - \sum_{NRC+1}^{NCV-1} \Delta P_I$$

Near the end of the first pass the pressure drop information for each control volume over a complete cycle is incorporated into the array of pressure ratios (discussed under step 4) for use in the second pass.

Heat Conduction From Hot End to Cold End of Engine and Shuttle Loss (Step 15):

Three separate paths were considered in the calculation of heat conduction losses from the hot end to the cold end of the engine:

(1) Through each of the regenerators

(2) Through the cylinder wall

(3) Through the wall of the piston from the hot space to the cold space

The effect of temperature on metal conductivity was accounted for.

The piston picks up heat from the cylinder at the hot end of its stroke and loses heat to the cylinder at the cold end of its stroke. This shuttle loss is calculated by using the following equation from reference 17:

$$Q_{shuttle} = \frac{K \pi D S^2 \Delta T}{8CL} \tag{26}$$

where

K thermal conductivity of gas

D piston diameter

S stroke

ΔT temperature difference across displacer length

C clearance between displacer and cylinder

L displacer length

The conduction and shuttle losses are calculated once per cycle. The calculations could be made just once per run except that the conduction through the piston is assumed to depend on the average gas temperature (The conduction through the piston is sufficiently small for the P-40 that a once per run calculation would yield very little error.)

Sum Up Heat Transfers Between Gas and Metal for Each Component (Step 16):

The basic heat into the working space per cycle is the sum of the net heat transfer from metal to gas in the heater and expansion-space control volumes over the cycle. The basic heat out of the working space per cycle is the sum of the net heat transfer from the gas to the metal in cooler and compression-space control volumes per cycle. Since it is assumed that there are no losses from the regenerator matrix, the net heat transferred between gas and metal in the regenerator over a cycle should be zero. This net heat transfer in the regenerator over the cycle is the most convenient criterion for judging when convergence of regenerator metal temperatures has been achieved.

The net heat into the engine is the basic heat (as defined above) plus conduction and shuttle losses. The net heat out of the engine is the basic heat out plus conduction, shuttle, appendix gap losses, mechanical losses and auxiliary power losses. Conduction, shuttle, appendix gap and mechanical losses (and any heat transfer out via the compression space) are assumed to pass into the cooling water but not through the cooler tubes (there are cooling water flow passages in contact with the cylinder). It is arbitrarily assumed that the auxiliary power requirement does not increase the heat load on the cooling water but is dissipated via convection and radiation to the surroundings.

Work Calculations (Step 17):

The indicated work, neglecting pressure drop loss, is calculated according to:

$$W = \oint P(dV_e + DV_c) \tag{27}$$

The indicated work, accounting for pressure drop loss, is calculated according to:

$$W = \oint (P_e dV_e + P_c\, dV_c) \tag{28}$$

From the volume equations for the P-40 engine, (6) and (7) it is found that

$$dV_e = A_p\ r \sin\alpha \left[1 + \frac{\frac{r}{L}\cos\alpha}{\sqrt{1 - \left(\frac{r}{L}\sin\alpha\right)^2}}\right] d\alpha$$

$$dV_c = -A_{pr} r \sin\left(\alpha + \frac{\pi}{2}\right)\left[1 + \frac{\frac{r}{L}\cos\left(\alpha + \frac{\pi}{2}\right)}{\sqrt{1 - \left(\frac{r}{L}\sin\left(\alpha + \frac{\pi}{2}\right)\right)^2}}\right] d\alpha$$

or, defining

$$F(P,A,\phi) = PAr\sin\phi\left[1 + \frac{\frac{r}{L}\cos\phi}{\sqrt{1 - \left(\frac{r}{L}\sin\phi\right)^2}}\right]$$

then

$$W = \oint (P_e dV_e + P_c dV_c)$$

$$= \oint \left[F(P_e, A_p, \alpha) + F\left(P_c, A_{pr}, \alpha + \frac{\pi}{2}\right)\right] d\alpha$$

$$= \quad f(\alpha)d\alpha$$

The above integration over a cycle was accomplished numerically using Simpson's rule integration, that is:

$$W\Big|_{\alpha_0}^{\alpha_2} = \int_{\alpha_0}^{\alpha_2} (P_e dV_e + P_c dV_c) = \int_{\alpha_0}^{\alpha_2} f(\alpha) d\alpha$$

$$= \frac{\Delta\alpha}{3}\left[f(\alpha_0) + 4f(\alpha_1) + f(\alpha_2)\right]$$

A number of additional work calculations were made to separate the work loss due to pressure drop for each of the components and for the end effects.

The chart in table XI shows how the various pressure and work parameters were made equivalent to arrays to allow reducing the number of programming steps required for the calculations; this chart is included only as an aid in following the FORTRAN programming steps of subroutine ROMBC.

Is Cycle Complete? (Step 18):

The number of iterations made during the current engine cycle is checked to see if the cycle is complete. If the cycle is not complete, then the model loops back to step 1 and another iteration is begun.

Convergence Method for Regenerator Metal Temperatures (Step 19):

The correction to regenerator matrix temperatures between cycles to speed up convergence (suggested by Jefferies, ref. 1) is made as follows:

$$\Delta T_I = \frac{\displaystyle\sum_{\mathrm{TIME}=0}^{\mathrm{TIME}=N\Delta t} (T_{w,I} - T_I)\left[1 - e^{-\left(\frac{h_I A_I}{M_I C_{p_I}}\right)\Delta t}\right] M_I}{\displaystyle\sum_{\mathrm{TIME}=0}^{\mathrm{TIME}=N\Delta t} \left[1 - e^{-\left(\frac{h_I A_I}{M_I C_{p_I}}\right)\Delta t}\right] M_I} \qquad I=NR1,NRL \qquad (29)$$

where

N number of iterations per cycle

ΔT_I weighted average difference between wall and gas temperature over cycle for Ith regenerator control volume

T_I Ith gas temperature (instantaneous average over control volume)

$T_{W,I}$ Ith wall temperature

Then let

$$\Delta T_I = \Delta T_{I,OLD} \times FACT_1 + \Delta T_I \times FACT_2 \qquad I=NR1,NRL$$

where FACT1 = 0.4 and FACT2 = 10.0 are the factors that were found to work best when the method was originally developed. (These factors were not re-optimized for the P-40 engine). The final step in the correction is:

$$T_{w,NR1,NEW} = T_{w,NR1,OLD} - (RC_{1,1} \times \Delta T_{NR1} + RC_{1,2} \times \Delta T_{NR1+1} + \dots + RC_{1,NR} \times \Delta T_{NRL})$$

$$T_{w,NR1+1,NEW} = T_{w,NR1+1,OLD} - (RC_{2,1} \times \Delta T_{NR1} + RC_{2,2} \times \Delta T_{NR1+1} + \dots + RC_{2,NR} \times \Delta T_{NRL})$$

....

....

$$T_{w,NRL,NEW} = T_{w,NRL,OLD} - (RC_{NR,1} \times \Delta T_{NR1} + RC_{NR,2} \times \Delta T_{NR1+1} + \dots + RC_{NR,NR} \times \Delta T_{NRL})$$

where the coefficients $RC_{i,k}$ are calculated as follows:

$$\text{For } k \geq i, \quad RC_{i,k} = \frac{(NR + 1 - k)NR}{\sum\limits_{k=1}^{NR} k} \qquad \text{if } i = 1$$

$$= i \times RC_{1,k} \qquad \text{if } i \neq 1$$

$$\text{for } k < i, \; RC_{i,k} = RC_{k,i}$$

For NR=5 (that is, 5 regenerator control volumes) the coefficients generated by the above equations are:

$$RC_{i,k} = \begin{bmatrix} \frac{5}{3} & \frac{4}{3} & 1 & \frac{2}{3} & \frac{1}{3} \\ \frac{4}{3} & \frac{8}{3} & 2 & \frac{4}{3} & \frac{2}{3} \\ 1 & 2 & 3 & 2 & 1 \\ \frac{2}{3} & \frac{4}{3} & 2 & \frac{8}{3} & \frac{4}{3} \\ \frac{1}{3} & \frac{2}{3} & 1 & \frac{4}{3} & \frac{5}{3} \end{bmatrix}$$

Caclulated Indicated Power and Efficiency (Step 20):

Indicated efficiency is defined to be the indicated work divided by the net heat into the engine (per cycle).

Calculate Mechanical (Plus Leakage) Loss (Step 21):

The mechanical loss calculations for the engine are based on information obtained from United Stirling.

The mechanical loss per engine (4 cylinders) is assumed to be:

$$M.L. = 12.8 \frac{N}{N_D} \frac{(P + 5)}{20}$$

where

M.L. mechanical loss/cylinder in KW
N engine speed
N_D design engine speed
P mean pressure in MPa

This "mechanical loss" is also assumed to include loss due to leakage. A plot generated with this equation is shown in figure 13.

Calculate Auxiliary Losses and Brake Power and Efficiency (Step 22):

A plot of the auxiliary power requirement is shown in figure 14. The only auxiliary power requirement assumed to change significantly with the mean pressure level is that of the combustion blower. The auxiliary power requirement for mean pressures between 15 and 4 MPa is obtained by interpolating between the two curves. The lower curve is assumed to define the minimum auxiliary power requirement.

Brake power is defined to be indicated power minus mechanical friction and auxiliary losses. Brake efficiency is defined to be the brake power divided by the net heat rate into the engine. The net heat rate into the engine is defined to be the net heat transfer from metal to gas in the heater and expansion space plus conduction and shuttle losses.

Convergence Method for Cooler Tube Temperatures (Step 23):

The cooler tube temperature is a function of cooling water inlet temperature and flow rate, and the rate of heat out through the cooler. Since the rate of heat out through the cooler is a function of cooler tube temperature, an iterative procedure is required to solve for cooler tube temperature.

The cooler tube temperature is updated every third cycle during the same period that the regenerator matrix temperature convergence procedure is operative. The procedure used is outlined as follows:

$$\overline{T}_{H_2O} = T_{H_2O,IN} + \frac{\dot{Q}_{H_2O,OUT}}{2C_{p,H_2O}\dot{W}_{H_2O}}$$

where

$\overline{T}_{H_2O}$	average coolant temperature
T_{H_2O}, IN	inlet coolant temperature
$\dot{Q}_{H_2O}$, OUT	rate of heat out through coolant
C_{P,H_2O}	coolant specific heat
$\dot{w}_{H_2O}$	coolant flow rate

Calculate water side heat transfer coefficient using the following two steps to incorporate a fouling factor:

1. $$h_1 = \frac{12k_{H_2O}}{.35D_o N_{Re}^{.55} N_{Pr}^{.333}}$$

2. $$h = \frac{1.}{\frac{1}{h_1} + 1.8}$$

where

h	heat transfer coefficient, incorporating a fouling factor
k_{H_2O}	thermal conductivity of coolant
N_{Re}	coolant Reynolds number
N_{Pr}	coolant Prandtl number
D_o	cooler tube outside diameter

The fouling factor 1.8 has units sec-ft 2-°R/Btu (0.881 cm^2-°K/w)
Calculate water side and cooler tube thermal resistances:

$$R_{H_2O} = \frac{1.}{hA_{HT}N_T}$$

$$R_{TUBE} = \frac{12\ \mathrm{LOG}\ \frac{D_{OD}}{D_{ID}}}{2\pi L_e N_T k_{ss}}$$

where

A_{HT}	water side heat transfer area per tube
N_T	no. of cooler tubes
L_e	effective heat transfer length of cooler tube
D_{ID}, D_{OD}	cooler tube inside and outside diameters, respectively
k_{ss}	cooler tube thermal conductivity

Then the cooler tube temperature is updated as follows:

$$T_{NEW} = \overline{T}_{H_2O} + 1.287\ E{-3}\ \dot{Q}_{H_2O,OUT}\ \omega(R_{H_2O} + R_{TUBE})$$

$$T_{NEW} = 0.5T_{NEW} + 0.5T_{OLD}$$

where

T_{NEW}	new tube temperature
T_{OLD}	old tube temperature
$\dot{Q}_{H_2O,OUT}$	rate of heat out through cooler
ω	engine frequency

The compression space wall temperature, TM_{NCV}, is then set as follows:

$$TM_{NCV} = T_{H_2O,IN} + 2(\overline{T}_{H_2O} - T_{H_2O,IN})$$

Have the Specified Number of Cycles (NOCYC) Been Completed? (Step 24):

A check is made to see if the specified number of cycles (NOCYC) has been completed. If not the model loops back to step 1. If, yes, then the procedure continues to the next step, 25, provided the two pass option, IPCV = 0, was specified (If a one pass option was chosen, IPCV = 1, then the procedure jumps to step 27, skipping steps 25 and 26).

Is This the Second Pass Through NOCYC Cycles? (Step 25):

A check is made to see if the the second pass was just completed. If not, the second pass is begun (step 26). If, yes, then the procedure continues to the final step, 27.

Second Pass Calculations (Step 26):

Time is reset to zero. The pressure drop information from the first pass is used in making working space thermodynamic calculations (instead of using a uniform pressure throughout the working space for these calculations) when the procedure loops back to step 1 and begins the second pass iterations.

Final Step (Step 27):

When the second pass is completed, if IPCV was set equal to 0, or the first pass is completed, if IPCV was set equal to 1, then the summary of predictions shown in table IX is written out. The model then attempts to read in a new set of operating conditions; if succesful, the entire calculation procedure of figure 11 is repeated; when no new operating conditions are found, the simulation is terminated.

APPENDIX B
DERIVATION OF GAS TEMPERATURE DIFFERENTIAL EQUATIONS

The basic gas volume equations used in the derivation are:

$$\frac{d}{dt}(MC_vT) = hA(T_w - T) + (C_{p_i}W_iT_i - C_{p_o}W_oT_o) - P\frac{dV}{dt} \tag{1}$$

$$\frac{dM}{dt} = W_i - W_o \tag{2}$$

$$PV = MRT \tag{3}$$

Expanding the first term of equation (1) gives:

$$MC_v\frac{dT}{dt} + C_vT\frac{dM}{dt} + MT\frac{dC_v}{dt} = hA(T_w - T) + (C_{p_i}W_iT_i - C_{p_o}W_oT_o) - P\frac{dV}{dt} \tag{B1}$$

Differentiating equation (3) gives:

$$MR\frac{dT}{dt} + RT\frac{dM}{dt} = P\frac{dV}{dt} + V\frac{dP}{dt} \tag{B2}$$

Letting $R = C_p - C_v$ in the first and second terms of equation (B2) and solving for

$$C_vT\frac{dM}{dt}$$

yields

$$C_vT\frac{dM}{dt} = M(C_p - C_v)\frac{dT}{dt} + C_pT\frac{dM}{dt} - P\frac{dV}{dt} - V\frac{dP}{dt} \tag{B3}$$

Substituting the right side of equation (B3) for the second term of equation (B1) yields:

$$\cancel{MC_v}\frac{dT}{dt} + M(C_p - \cancel{C_v})\frac{dT}{dt} + C_pT\frac{dM}{dt} - P\cancel{\frac{dV}{dt}} - V\frac{dP}{dt} + MT\frac{dC_v}{dt}$$

$$= hA(T_w - T) + (C_{p_i}W_iT_i - C_{p_o}W_oT_o) - P\cancel{\frac{dV}{dt}}$$

or

$$MC_p \frac{dT}{dt} + C_p T \frac{dM}{dt} - V \frac{dP}{dt} + MT \frac{dC_v}{dt} = hA(T_w - T) + (C_{p_i} W_i T_i - C_{p_o} W_o T_o) \qquad \text{(B4)}$$

Using equation (2) to substitute for dM/dt in equation (B4) and also substituting

$$\frac{dC_v}{dt} = \frac{dC_p}{dt} \quad \text{in (B4)}$$

then solving for $MC_p \frac{dT}{dt}$ gives

$$MC_p \frac{dT}{dt} = hA(T_w - T) + (W_o - W_i)C_p T + (C_{p_i} W_i T_i - C_{p_o} W_o T_o) + V \frac{dP}{dt} - MT \frac{dC_p}{dt} \qquad (4)$$

which is the equation used in the model to solve for gas temperature.

APPENDIX C

INTEGRATION OF DECOUPLED TEMPERATURE EQUATIONS

Temperature time derivative due to change in specific heat:

$$\frac{dT}{dt}\Big|_{\substack{\text{due to}\\\text{change in}\\\text{specific heat}}} = -\frac{T}{C_p}\frac{dC_p}{dt} \tag{5a}$$

$$\therefore \frac{dT}{T} = -\frac{dC_p}{C_p}$$

Integrating -

$$\mathrm{LN}\ T\Big|_{t}^{t+\Delta t} = -\ \mathrm{LN}\ C_p\Big|_{t}^{t+\Delta t}$$

$$\therefore \mathrm{LN}\ \frac{T^{t+\Delta t}}{T^{t}} = \mathrm{LN}\ \frac{C_p^{t}}{C_p^{t+\Delta t}}$$

$$\therefore T^{t+\Delta t} = T^{t}\ \frac{C_p^{t}}{C_p^{t+\Delta t}}$$

Temperature time Derivative Due to Pressure Change:

The equation

$$\frac{dT}{dt}\Big|_{\substack{\text{due to}\\\text{change in}\\\text{pressure}}} = \frac{V}{MC_p}\frac{dP}{dt} \tag{5b}$$

can be integrated in closed form (if it is assumed that C_p is constant over the time increment) by solving the equation of state for V/M and substituting in equation (5b).

$$PV = MRT \rightarrow \frac{V}{M} = \frac{RT}{P}$$

Substituting

$$\frac{dT}{dt} = \frac{RT}{PC_p}\frac{dP}{dt}$$

$$\frac{dT}{T} = \frac{R}{C_p}\frac{dP}{P}$$

Assuming C_p is constant over Δt and integrating -

$$LN\ T\Big|_{t}^{t+\Delta t} = \frac{R}{C_p} LN\ P\Big|_{t}^{t+\Delta t}$$

$$\therefore \quad \frac{T^{t+\Delta t}}{T^t} = \left(\frac{P^{t+\Delta t}}{P^t}\right)^{\frac{R}{C_p^{t+\Delta t}}}$$

$$\therefore \quad T^{t+\Delta t} = T^t\left(\frac{P^{t+\Delta t}}{P^t}\right)^{\frac{R}{C_p^{t+\Delta t}}}$$

For the second pass it is assumed that P is the pressure in the center of the regenerator and a pressure ratio factor (ratio of pressure at the control volume of interest to pressure in the center of the regenerator) is introduced to better account for the influence of pressure drop on the heat transfer calculations. Introducing the array of pressure ratios, F, into the above equation the result is:

$$T^{t+\Delta t} = T^t\left(\frac{P^{t+\Delta t}F^{t+\Delta t}}{P^tF^t}\right)^{\frac{R}{C_p^{t+\Delta t}}}$$

(Each element of this array, F, is set equal to 1 during the first pass.)

<u>Temperature Time Derivative Due to Mixing</u>:

$$\frac{dT}{dt}\underset{\text{mixing}}{\text{due to}} = \frac{\left(W_o - W_i\right) C_pT + \left(C_{p_i}W_iT_i - C_{p_o}W_oT_o\right)}{MC_p} \tag{5C}$$

Using numerical integration let

$$T^{t+\Delta t} = T^t + \frac{dT}{dt} \; \Delta t$$

$$\therefore \quad T^{t+\Delta t} = T^t + \frac{\left(W_o^{t+\Delta t} - W_i^{t+\Delta t}\right) C_p^{t+\Delta t} T^t + \left(C_{p_i}^{t+\Delta t} W_i^{t+\Delta t} T_i^{t+\Delta t} - C_{p_o}^{t+\Delta t} W_o^{t+\Delta t} T_o^{t+\Delta t}\right)}{M^{t+\Delta t} C_p^{t+\Delta t}} \; \Delta t$$

Substituting

$$\left(W_o^{t+\Delta t} - W_i^{t+\Delta t}\right) = \frac{M^t - M^{t+\Delta t}}{\Delta t}$$

$$T^{t+\Delta t} = \frac{M^t}{M^{t+\Delta t}} T^t + \frac{\left(C_{p_i}^{t+\Delta t} W_i^{t+\Delta t} T_i^{t+\Delta t} - C_{p_o}^{t+\Delta t} W_o^{t+\Delta t} T_o^{t+\Delta t}\right)}{M^{t+\Delta t} C_p^{t+\Delta t}} \; \Delta t$$

Temperature Time Derivative Due to Heat Transfer:

$$\left.\frac{dT}{dt}\right|_{\text{due to heat transfer}} = \frac{hA}{MC_p}(T_w - T) \rightarrow \frac{dT}{T_w - T} = \frac{hA}{MC_p} \; dt \qquad (5d)$$

Assume T_w is constant over the time step for the purpose of integrating the left side with respect to time. This is a reasonable assumption since T_w changes much more slowly than T due to the relatively large heat capacity of the metal. It was also assumed that h and M were constant over the time step to allow integration of the right side of the equation.

$$-LN(T_w - T)\Big|_t^{t+\Delta t} = \frac{hA}{MC_p} \, t \Big|_t^{t+\Delta t}$$

$$LN \frac{(T_w - T)^{t+\Delta t}}{(T_w - T)^t} = -\frac{hA}{MC_p} \; \Delta t$$

$$\therefore \quad (T_w - T)^{t+\Delta t} = (T_w - T)^t e^{-\frac{hA}{MC_p} \Delta t}$$

$$\therefore \quad T^{t+\Delta t} = T_w - (T_w - T)^t \, e^{-\frac{hA}{MC_p}\Delta t}$$

$$T^{t+\Delta t} = T^t + (T_w - T^t)\left(1 - e^{-\frac{hA}{MC_p}\Delta t}\right)$$

This equation says that, as the time step is made larger, the gas temperature approaches the wall temperature asymptotically. Thus using large time steps cannot cause instabilities because of excessive change in gas temperature.

APPENDIX D

EXPANSION AND COMPRESSION SPACE HEAT TRANSFER COEFFICIENTS

EXPANSION SPACE

This analysis assumes perfect insulation between the combustion gas and the expansion space wall. Heat transfer between the expansion space wall and the working space gas is a combination of radiation and convection. For radiation:

$$\frac{Q}{A} = \sigma F\left(T_w^4 - T^4\right)$$

and

$$h_{rad} = \frac{\frac{Q}{A}}{T_w - T} \tag{D1}$$

where

σ	Boltzmann constant
F	emissivity times view factor
T_w	wall temperature
T	gas temperature
Q	rate of heat flow
A	heat transfer area
h_{rad}	radiation heat-transfer coefficient

The overall F is assumed to be 0.7

The convection heat-transfer coefficient is:

$$h_{conv} = 0.023(Re)^{0.8}(Pr)^{0.4}\frac{k}{D_h} \qquad Re > 10\ 000$$

or (D2a)

$$h_{conv} = 0.023(Re)^{0.8}(Pr)^{0.4}\frac{k}{D_h}\left[1 + \left(\frac{D_h}{L}\right)^{0.07}\right] \qquad 2100 < Re \leq 10\ 000$$

where L is the maximum distance from the cylinder head to the displacer, and

$$h_{conv} = 1.86(GRAETZ)^{0.333}\frac{k}{D_h} \qquad GRAETZ > 10;\ Re \leq 2100 \tag{D2b}$$

or

$$h_{conv} = 5.0 \text{ Btu/hr} - \text{ft}^2 - {}^\circ\text{R} \left(28.4 \frac{\text{W}}{\text{M}^2 - \text{K}}\right) \qquad \text{GRAETZ} \leq 10;\ \text{Re} \leq 2100 \quad \text{(D2c)}$$

where Graetz number = Re X Pr X DH/L. The value in equation (D2c) is an assumed cutoff point (close to the natural convection coefficient). For the combined heat-transfer coefficient the values obtained from equations (D1) and (D2) are added

Compression Space

Since the radiation effect is small in the compression space, only convection heat transfer is considered. Equation (D2) is used for the calculation. It is assumed that the wall temperature is known. Without detailed analysis or test data to identify this wall temperature, it seems reasonable to assume that it is about equal to the average compression space gas temperature over the cycle. The net result is that very little heat transfer takes place in the compression space and the compression-space process is essentially adiabatic.

APPENDIX E
MOMENTUM EQUATION AND DECOUPLED PRESSURE DROP CALCULATIONS
MOMENTUM EQUATION

A general form of the conservation of momentum equation for one-dimensional flow is:

$$\frac{\partial}{\partial t}(\rho v) \quad + \frac{\partial}{\partial x}(\rho v^2) \quad + \frac{f}{2D_h}\rho v^2 \quad + \frac{\partial P}{\partial x} \quad = 0 \tag{E1}$$

Rate of accumulation of momentum per unit volume	Rate of momentum gain by convection per unit volume	Rate of momentum gain by viscous transport per unit volume	Rate of momentum gain by pressure force per unit volume

Expanding the first and second terms of equation (E1) yields:

$$\rho\frac{\partial v}{\partial t} + V\frac{\partial \rho}{\partial t} + V\frac{\partial(\rho v)}{\partial x} + \rho v\frac{\partial v}{\partial x} + \frac{f}{2D_h}\rho v^2 + \frac{\partial P}{\partial x} = 0 \tag{E2}$$

By the continuity equation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho v) = 0$$

Therefore the second the third terms of equation (E2) can be eliminated to yield:

$$\rho\frac{\partial v}{\partial t} + \rho v\frac{\partial v}{\partial x} + \frac{f}{2D_h}\rho v^2 + \frac{\partial P}{\partial x} = 0 \tag{E3}$$

The first term in equation (E3) is neglected in the model. Neglecting this term and multiplying the resulting equation by $\partial x/\rho$ yields:

$$v\partial v + \frac{f}{2D_h}v^2\partial x + \frac{\partial P}{\rho} = 0 \tag{E4}$$

Note that at zero flow the second and third terms of equation (E3) are zero, so that it reduces to

$$\rho \frac{\partial v}{\partial t} + \frac{\partial P}{\partial x} = 0$$

in which case the time derivative term is responsible for any pressure drop. The significance of this time derivative term could be investigated by the use of a model which uses the complete momentum equation such as that of Urieli (ref. 18) or that of Schock (ref. 19).

Decoupled Pressure Drop Calculations:

The pressure drop calculations are decoupled from the basic thermodynamic calculations for the working space; this decoupling of pressure drop allows use of a larger time step (and less computing time) than would otherwise be possible with the explicit, one iteration per time step, numerical integration used in the model.

The effect of pressure drop on the thermodynamic calculations is accounted for as follows:

(1) Engine work, heat in and heat out per cycle are calculated assuming no pressure drop. Pressure variation with time over the cycle is the same at all control volumes in the working space. Gas flow rates are, therefore, dependent only on the variable volumes and the fluctuations in the working space gas temperatures.

(2) Using the "no pressure drop" gas flow rates calculated in step (1) above, pressure drops are calculated across each control volume; the pressure variation with time at the center of the regenerator is the same as in step (1).

(3) The pressure drops calculated in step (2) are summed up from the expansion space to the center of the regenerator and from the center of the regenerator to the compression space at each time step. Pressure variations for expansion and compression space are corrected for pressure drop.

(4) The Δp corrected pressure variations in the expansion and compression spaces are used to recalculate expansion space work, compression space work and total engine work per cycle. The difference between the works calculated in (1), assuming no Δp, and the Δp corrected works yield:

(a) total work loss per cycle due to Δp

(b) work loss from expansion space to the center of the regenerator (hot side of working space) due to Δp.

(c) work loss from center of regenerator to compression (cold side of working space) due to Δp.

(5) The heat into the engine is now corrected for Δp by assuming:

$$\left.\begin{array}{l}\text{Heat}\\ \text{into}\\ \text{engine}\end{array}\right|_{\text{with } \Delta P} = \left.\begin{array}{l}\text{Heat}\\ \text{into}\\ \text{engine}\end{array}\right|_{\text{without } \Delta P} - \begin{array}{l}\text{Work loss}\\ \text{due to } \Delta P\\ \text{on hot side of}\\ \text{working space}\end{array}$$

The heat out of the engine is corrected by assuming:

$$\left.\begin{array}{l}\text{Heat}\\ \text{out of}\\ \text{engine}\end{array}\right|_{\text{with } \Delta P} = \left.\begin{array}{l}\text{Heat}\\ \text{out of}\\ \text{engine}\end{array}\right|_{\text{without } \Delta P} + \begin{array}{l}\text{Work loss}\\ \text{due to } \Delta P\\ \text{on cold side of}\\ \text{working space}\end{array}$$

All calculations up to this point are completed during the first NOCYC = 25 cycle pass through the model calculations. The Δp corrections discussed above were the only ones made in the model of reference 1. An improved correction for the effect of Δp has been incorporated into the model by adding the following steps to the above:

(6) During the last cycle of the first pass, store the pressure variations over the cycle, corrected for Δp, for each control volume. A convenient way to do this is to store the ratio of pressure at the control volume to pressure at the center of the regenerator, for each control volume at each time step over the cycle. Thus an array of pressure ratios is created which documents the effect of Δp on the pressure variations at each control volume over the cycle.

(7) A second pass (of NOCYC = 25 more cycles) is made through the model calculations. This time, instead of assuming a uniform pressure variation with time throughout the working space in making the thermodynamic calculations, the array of pressure ratios is used to infer pressure variation, corrected for Δp, at each control volume. A calculation of engine work with no Δp (that is doing the expansion and compression space work integrations using the pressure at the center of the regenerator) is still made to allow a calculation of work loss due to Δp. Now, however, the correction to the heat transfer in and out over the cycle (as in (5)) is no longer necessary; this is because the effect of pressure drop (via the pressure variations at each control volume over the cycle) is now an integral part of the heat and mass transfer calculations at each time step.

The second pass through the calculations does not significantly change the calculated work loss due to Δp. However, the heat into the heater (and the expansion space work) increases more than the heat out of the cooler (and the compression space work). Thus there is a net increase in the basic work and power (that is, work and power before Δp loss) calculated for the engine. For hydrogen at design P-40 conditions (15 MPa, 4000 RPM) the effect of the second pass was to increase brake power by 1.2 kW (3.5%). For helium at design P-40 conditions the increase is about 1.9 kW (9.7 percent). Since the model usually overpredicts power, the additional correction increases the error in predicted power at the design point; it did, however, cause the shape of the predicted curve to approximate more closely that of the experimental curve.

In developing the second pass correction, it was found that recalculating the pressure ratio array, F, at the end of the second and then making a third pass had negligible effect on the predicted performance. No attempt was made to optimize the correction procedure to get minimum computing time. For example, it may be possible to use fewer cycles during the first pass and get the same accuracy.

APPENDIX F: SYMBOLS USED IN FORTRAN SOURCE PROGRAMS, INPUT DATA SETS, AND OUTPUT DATA SETS

A	Ratio of inlet and outlet areas for flow coefficient calculation
AC	Compression space work per increment of crank angle, ft-lbf/rad (J/rad)
ACAN	Heat conduction area for external insulation container, in^2 (CM^2)
ACDUC	Compression space work, with only cooler pressure drop, per increment of crank angle, ft-lbf/rad (J/rad)
ACDUE	Compression space work, with only end-effects pressure drop, per increment of crank angle, ft-lbf/rad (J/rad)
ACDUR	Compression space work, with only regenerator pressure drop, per increment of crank angle, ft-lbf/rad (J/rad)
ACONDD	Heat conduction area through piston, in^2 (cm^2)
ACO2	Coefficient in quadratic equation for specific heat of carbon dioxide, Btu/lbm-°R (J/kg-K)
ACP	Compression space work with no pressure drop per increment of crank angle, ft-lbf/rad (J/rad)
ACS	Array of control volume cross-sectional flow areas, in^2/regenerator flow path (cm^2/regenerator flow path)
ACSCOM	Effective compression space cross-sectional flow area, used for end effects pressure drop calculation, in^2 (cm^2)
ACSEXP	Effective expansion space cross-sectional flow area, used for end effects pressure drop calculation, in^2 (cm^2)
ACSO	Alternate storage array for array ACS
AE	Expansion space work per increment of crank angle, ft-lbf/rad (J/rad)
AEALT	Expansion space work per increment of crank angle if all pressure drop is calculated relative to the pressure in the compression space, ft-lbf/rad (J/rad)
AEDUE	Expansion space work, with only end effects pressure drop considered, per increment of crank angle, ft-lbf/rad (J/rad)
AEDUH	Expansion space work, with only heater pressure drop considered, per increment of crank angle, ft-lbf/rad (J/rad)
AEDUR	Expansion space work , with only regenerator pressure drop considered, per increment of crank angle, ft-lbf/rad (J/rad)

AEFH2O	Effective cooling water flow area through coolers per cylinder, in^2 (cm^2)
AEP	Expansion space work, assuming no pressure drop, per increment of crank angle, ft-lbf/rad (J/rad)
AHE	Temperature independent term in equation for specific heat at constant volume for helium, in-lbf/lbm-°R (J/kg-K)
AHT	Array of control volume heat transfer areas, in^2/regenerator flow path (cm^2/regenerator flow path)
AHTCTW	Heat transfer area of one cooler tube on the water side, ft^2 (cm^2)
AHTO	Alternate storage array for array AHT
AH2	Temperature independent term in equation for specific heat at constant volume for hydrogen, in-lbf/lbm-°R (J/kg-K)
AIN	Inlet flow area, ft^2 (cm^2)
ALPHA	Crank angle, rad
AMIN	Ratio of inlet and outlet areas
ANGLE	Dummy variable used in work integral function definition, rad
AOUT	Outlet flow area, ft^2 (cm^2)
AP	Piston cross-sectional area, in^2 (cm^2)
APCMAX	Crank angle at which maximum compression space pressure occurs, deg
APCMIN	Crank angle at which minimum compression space pressure occurs, deg
APEMAX	Crank angle at which maximum expansion space pressure occurs, deg
APEMIN	Crank angle at which minimum expansion space pressure occurs, deg
APMAR	Piston cross-sectional area minus piston rod cross-sectional area, in^2 (cm^2)
AR	Piston rod cross-sectional area, in^2 (cm^2)
AREA	Dummy variable used in work integral function definition, in^2
AREAIN	inlet flow area, in^2 (cm^2)
AREAOT	Outlet flow area, in^2 (cm^2)
AS	Array of variables equivalent to works per increment of crank angle in COMMON /ASET/, ft-lbf/rad (J/rad)
ATPC	Total work per increment of crank angle when pressure drop is calculated relative to compression space pressure, ft-lbf/rad (J/rad)
AUXEFF	Engine efficiency, including auxiliary losses
AUXFP1	Auxiliary power requirement per cylinder, ft-lbf/cycle (J/cycle)
AUXFP4	Auxiliary power requirement for engine, ft-lbf/cycle (J/cycle)

AUXHP4	Auxiliary power requirement for engine, hp (kW)
AUXKW4	Auxiliary power requirement for engine, kW
AUXLOS	Auxiliary power requirement per cylinder, hp (kW)
AUXPWR	Engine brake power (with auxiliary power requirement subtracted), hp (kW)
AVGPC	Time averaged compression space pressure, lbf/in^2 (N/cm^2)
AVGPE	Time averaged expansion space pressure, lbf/in^2 (N/cm^2)
AVGPMP	Time averaged pressure at center of regenerator, MPa
AVGWSP	Time averaged pressure at center of regenerator, lbf/in^2 (N/cm^2)
AVPCMP	Average compression space pressure, MPa
AVPEMP	Average expansion space pressure, MPa
A1	Temperature independent term in equation for specific heat at constant volume, in-lbf/lbm-°R (J/kg-K)
B	Coefficient, real gas equation of state, lbf/in^2 (N/cm^2)
BASICP	Indicated power plus pressure drop loss, per cylinder, hp (kW)
BCO2	Coefficient in quadratic equation for specific heat of carbon dioxide, BTU/lbm-$°R^2$ (J/kg-K^2)
BETA	Crank angle +PI/2, rad
BHE	Sensitivity of specific heat at constant volume to temperature for helium, in-lbf/lbm-$°R^2$ (J/kg-K^2)
BH2	Sensitivity of specific heat at constant volume to temperature for hydrogen, in-lbf/lbm-$°R^2$ (J/kg-K^2)
BPFP1	Engine brake power per cylinder, ft-lbf/cycle (J/cycle)
BPFP4	Engine brake power, ft-lbf/cycle (J/cycle)
BPHP1	Engine brake power per cylinder (=AUXPWR), hp (kW)
BPHP4	Engine brake power, hp (kW)
BPKW1	Engine brake power per cylinder, kW
BPKW4	Engine brake power, kW
BRKEFF	Engine brake efficiency (not including effect of auxiliaries)
BRKP	Engine brake power per cylinder (not accounting for auxiliaries losses), hp (kW)
B1	Sensitivity of specific heat at constant volume to temperature, in-lbf/lbm-°R (J/kg-K)
CANIR	Insulation container inside radius, in (cm)
CANOR	Insulation container outside radius, in (cm)
CCMPDV	Cooler-compression space connecting duct volume, in^3 (cm^3)

CCO2	Coefficient in quadratic equation for specific heat of carbon dioxide, Btu/lbm-°R^3 (J/kg-K^3)
CDEDV	Cooler dead volume per cylinder, in^3 (cm^3)
CFACTR	Function of average working space pressure used in calculating auxiliary loss, dimensionless
CHCF	Cooler heat transfer coefficient multiplying factor
CHCFAC	Cooler heat transfer coefficient multiplying factor
CHE	Coefficient in equation for specific heat of helium, Btu/lbm-°R^3 (J/kg-K^3)
CH2	Coefficient in equation for specific heat of hydrogen, Btu/lbm-°R^3 (J/kg-K^3)
CH2P	Monatomic thermal conductivity of hydrogen, Btu/in-sec °R (W/cm-K)
CH2PP	Internal thermal conductivity of hydrogen, Btu/in-sec °R (W/cm-K)
CLRLOD	Cooler tube length to diameter ratio
CMIXP	Monatomic thermal conductivity of mixture of hydrogen and carbon dioxide, Btu/in-sec-°R (W/cm-K)
CMIXPP	Internal thermal conductivity of mixture of hydrogen and carbon dioxide, Btu/in-sec-°R (W/cm-K)
CMPSCL	Compression space clearance volume, in^3 (cm^3)
CNDH2O	Thermal conductivity of water, Btu/ft-sec-°R (W/cm-K)
CNDSS	Cooler tube (stainless steel) thermal conductivity, Btu/ft-sec-°R (W/cm-K)
COEF	Pressure drop coefficient, dimensionless
COEFX	Pressure drop coefficient, dimensionless
COND	Array of control volume gas thermal conductivities, Btu/in-sec-°R (W/cm-K)
CONDT	Heater tube thermal conductivity, Btu/in-sec-°R (W/cm-K)
CONDTB	Conduction length, top to bottom, of external insulation container (if used), in (cm)
CO2P	Monatomic thermal conductivity of carbon dioxide, Btu/in-sec-°R (W/cm-K)
CO2PP	Internal thermal conductivity of carbon dioxide, Btu/in-sec-°R (W/cm-K)
CP	Array of control volume interface specific heats at constant pressure, Btu/lbm-°R (J/kg-K)

CPA	Array of control volume specific heats at constant pressure, Btu/lbm-°R (J/kg-K)
CPAO	Alternate storage array for array CPA
CPCGP	Specific heat in cold appendix gap, Btu/lbm-°R (J/kg-K)
CPCGPI	Specific heat of gas crossing interface between cold appendix gap and compression space, Btu/lbm-°R (J/kg-K)
CPCYC	Time increments (iterations) per engine cycle
CPHGP	Specific heat in hot appendix gap, Btu/lbm-°R (J/kg-K)
CPHGPI	Specific heat of gas crossing interface between hot appendix gap and expansion space, Btu/lbm-°R (J/kg-K)
CPH2O	Cooling water specific heat, Btu/lbm-°R (J/kg-K)
CPM	Regenerator matrix specific heat, Btu/lbm-°R (J/kg-K)
CR1	Initialization constant
CR2	Initialization constant
CR3	Initialization constant
CTBID	Cooler tube inside diameter, in (cm)
CTBL	Cooler tube length, in (cm)
CTBOD	Cooler tube outside diameter, in (cm)
CTBPCN	Cooler tubes per cylinder
CV	Array of control volume specific heats at constant volume, Btu/lbm-°R (J/kg-K)
CVF	Function for calculating specific heat at constant volume, Btu/lbm-°R (J/kg-K)
CYLDMB	Cylinder distance between middle and bottom wall temperatures, in (cm)
CYLDTM	Cylinder distance between top and middle wall temperatures, in (cm)
CYLIR	Cylinder housing inside radius, in (cm)
CYLORB	Cylinder outside radius at bottom temperature, in (cm)
CYLORM	Cylinder outside radius at middle temperature, in (cm)
CYLORT	Cylinder outside radius at top temperature, in (cm)
DALOSS	Design auxiliary loss--four cylinders, hp (kW)
DE	Hydraulic diameter, ft (cm)
DELP	Array of pressure drops across control volumes, lbf/in^2 (N/cm^2)
DELPCL	Pressure drop across cooler, lbf/in^2 (N/cm^2)
DELPHT	Pressure drop across heater, lbf/in^2 (N/cm^2)
DELPRG	Pressure drop across regenerator, lbf/in^2 (N/cm^2)
DELTIM	Engine cycle period, sec

DELTM	Change in regenerator matrix temperature from one control volume to the next, °R (K)
DFLOSS	Design mechanical friction loss, hp (kW)
DFREQ	Design engine frequency, Hz
DGAPDV	Piston-cylinder gap dead volume, in^3 (cm^3)
DH	Array of control volume hydraulic diameters, in (cm)
DHO	Alternate storage array for array DH, in (cm)
DHX	Hydraulic diameter, in (cm)
DISPD	Piston diameter, in (cm)
DISPRD	Piston rod diameter, in (cm)
DNSTY	Array of control volume gas densities, lbm/in^3 (kg/cm^3)
DP	Pressure drop, lbf/in^2 (N/cm^2)
DPCLR	Cooler pressure drop, lbf/in^2 (N/cm^2)
DPECLD	End effects pressure drop, cold side of engine, lbf/in^2 (N/cm^2)
DPEHOT	End effects pressure drop, hot side of engine, lbf/in^2 (N/cm^2)
DPFRIC	Total pressure drop excluding end effects, lbf/in^2 (N/cm^2)
DPHTR	Heater pressure drop, lbf/in^2 (N/cm^2)
DPRCLD	Regenerator pressure drop, cold side, lbf/in^2 (N/cm^2)
DPRHOT	Regenerator pressure drop, hot side, lbf/in^2 (N/cm^2)
DPSI	Crank angle increment, rad
DPSUM	Total pressure drop, lbf/in^2 (N/cm^2)
DPX	Array of pressure drops, lbf/in^2 (N/cm^2)
DRPM	Design engine speed, rpm (Hz)
DSPGAP	Gap width between piston and displacer, in (cm)
DSPHGT	Piston height (used in piston-cylinder gap dead volume calculation), in (cm)
DSPWTH	Piston wall thickness, in (cm)
DTCGP	Change in cold appendix temperature that would occur due to change in pressure (if appendix gap were not isothermal), °R (K)
DTCYL	Cylinder housing temperature difference between thermocouple locations, when calculated by code, °R (K)
DTGA	Change in control volume gas temperature due to heat transfer between gas and metal, °R (K)
DTGASL	One-half of the assumed change in gas temperature across the regenerator control volume, °R (K)

DTHGP Change in hot appendix gap gas temperature that would occur due to change in pressure level, °R (K)

DTIME Time increment, sec

DTM Array of regenerator matrix temperature corrections, °R (K)

DTREG Regenerator housing temperature difference between thermocouple locations, when calculated by code, °R (K)

DWCMP Increment in compression space work for one crank angle increment, ft-lbf (J)

DWEXP Increment in expansion space work for one crank angle increment, ft-lbf (J)

E Crank eccentricity (was used in rhombic drive simulation)

ECTBL Effective cooler tube length for heat transfer, in (cm)

EFFTOT Engine indicated efficiency

EHTBL Effective heater tube length for heat transfer, in (cm)

EID Engine identification (alphanumeric)

ENFCTR Enthalpy flow from cooler to regenerator per cycle, Btu (J)

ENFHTR Enthalpy flow from heater to regenerator per cycle, Btu (J)

ENFRTC Enthalpy flow from regenerator to cooler per cycle, Btu (J)

ENFRTH Enthalpy flow from regenerator to heater per cycle, Btu (J)

EN3PM Rate at which working space volume is swept out, in^3/min (cm^3/min)

ETYPE Engine type

EXPHDV Expansion space-heater connecting duct volume, in^3 (cm^3)

EXPSCL Expansion space clearance volume, in^3 cm^3)

F Array of flow rates at control volume interfaces, lbm/sec (kg/sec)

FACT1 Coefficient used in regenerator matrix temperature convergence method

FACT2 Coefficient used in regenerator matrix temperature convergence method

FAVG Array of average flow rates for each control volume, lbm/sec (kg/sec)

FAVG2 Average control volume gas flow rate, lbm/sec (kg/sec)

FCGP Flow rate between compression space and cold appendix gap, lbm/sec (kg/sec)

FCND1,FCND11,FCND12 Functions of mass fractions and thermal conductivity of pure gases used in calculating thermal conductivity of mixture of gases

FCND2,FCND21,FCND22 Functions of mass fractions of pure gases used in calculating thermal conductivity of mixture of gases

FCNPP1,FCNPP2 Functions of mass fractions and thermal conductivity of pure gases used in calculating thermal conductivity of mixture of gases

FCTR Dimensionless function of heat transfer between gas and metal

FDEN Parameter used in calculating matrix of coefficients for regenerator matrix temperature convergence method

FHGP Flow rate between expansion space and hot appendix gap, lbm/sec (kg/sec)

FICLR Gas flow rate at hot end of cooler per cylinder, lbm/sec (kg/sec)

FIHTR Gas flow rate at hot end of heater per cylinder, lbm/sec (kg/sec)

FIJ,FIJ1,FIJ2 Functions of mass fractions and viscosities of pure gases for calculating viscosity of a mixture of gases

FIK Array of--control volume pressure/pressure at center of regenerator--(values for each time increment over cycle)

FIKS Alternate storage array for array FIK

FIPCV On-off switch used to modify calculation of heat out and heat into engine

FIREG Gas flow rate at hot end of regenerator per cylinder, lbm/sec (kg/sec)

FLFP1 Friction loss per cylinder, ft-lbf/cycle (J/cycle)

FLFP4 Friction loss for engine, ft-lbf/cycle (J/cycle)

FLHP4 Friction loss for engine, hp (kW)

FLKW4 Friction loss for engine, kW

FLOH2O Cooling water flow flow rate per cylinder, lbm/sec (kg/sec)

FLOPUA Cooling water flow rate per unit cross-sectional area, lbm/sec-in^2 (kg/sec-cm^2)

FLOW Absolute value of gas flow rate per regenerator flow path, lbm/sec (kg/sec)

FLOWIN Gas flow rate per regenerator flow path, lbm/sec (kg/sec)

FMA21 Function of inlet and outlet Mach numbers, dimensionless

FMULT Multiplier for overall pressure drop

FMULTR Multiplier for regenerator pressure drop

FNUM Parameter used in calculating matrix of coefficients for regenerator matrix temperature convergence method

FOA Estimate of effectiveness of radiation heat transfer from metal to gas in expansion space (emissivity * view factor)

FOCLR Gas flow rate at cold end of cooler per cylinder, lbm/sec (kg/sec)

FOEXP Gas flow rate at exit of expansion space, lbm/sec (kg/sec)

FOHTR	Gas flow rate at cold end of heater per cylinder, lbm/sec (kg/sec)
FOREG	Gas flow rate at cold end of regenerator per cylinder, lbm/sec (kg/sec)
FREQ	Engine speed, Hz
FRIN	Gas flow rate at hot end of regenerator per cylinder, lbm/sec (kg/sec)
FRLOSS	Friction loss per cylinder, hp (kW)
FO	Variable used in definition of function for Simpson rule integration (value of integrand at two time increments before current time)
F1	Variable used in definition of function for Simpson rule integration (value of integrand at one time increment before current time)
F2	Variable used in definition of function for Simpson rule integration (value of integrand at current time)
GAMMA	Ratio of gas specific heats (CP/CV)
GAMMA1	=GAMMA for adiabatic flow, =1.0 for isothermal flow
GPMH2O	Cooling water flow rate per cylinder, gal/min (gm/sec)
GRAETZ	Dimensionless number for calculating convection heat transfer in expansion space
GRAV	Constant, 32.2 lbm-ft/lbf-sec^2 (1.0 kg-M/N-sec^2)
H	Array of gas to metal heat transfer coefficients, Btu/sec-in^2-°R in subroutine HEATX (W/cm^2-K) units converted to Btu/sec-ft^2-°R in subroutine ROMBC
HA	Array of--heat transfer coefficients * heat transfer area--between gas and wall), Btu/sec-°R (W/K)
HACYC	Array of average heat transfer coefficients over the engine cycle, Btu/sec-ft^2-°R (W/cm^2-K)
HAWC	Dimensionless ratio--(heat transfer between gas and wall per deg of temperature difference)/(control volume heat capacity)
HCONV	Convection heat transfer coefficient in expansion space, Btu/sec-in^2-°R (W/cm^2-°K)
HDEDV	Heater dead volume per cylinder, in^3 (cm^3)
HFACT	Dimensionless factor used in calculating heat transfer coefficients
HHCF	Dimensionless factor used in calculating heater heat transfer coefficients
HHCFAC	Heater heat transfer coefficient multiplying factor
HLOD	Array of heat transfer coefficient function values for different tube length/diameter ratios, dimensionless

HMX	Array of maximum values of heat transfer coefficients over the cycle, Btu/sec-ft^2-°R (W/cm^2-K)
HRAD	Effective heat transfer coefficient for radiation heat transfer in expansion space, Btu/sec-in^2-°R (W/cm^2-K)
HRDV	Heater-regenerator connecting duct volume, in^3 (cm^3)
HTABL	Table of values of heat transfer correlation, dimensionless
HTBID	Heater tube inside diameter, in (cm)
HTBL	Heater tube length, in (cm)
HTBOD	Heater tube outside diameter, in (cm)
HTBPCN	Number of heater tubes per cylinder
HTRLOD	Heater tube length over diameter ratio
HWATR1	Clean tube, cooler tube to water heat transfer coefficient, Btu/sec-ft2-°R (W/cm^2-K)
HWATR2	Fouled tube, cooler tube to water heat transfer coefficient, Btu/sec-ft^2-°R (W/cm^2-K)
I	Index
ICOND	Index; =1 calculate cylinder and regenerator housing temperatures from TM(1), TM(4), and TH2OIN, =0 use input values for housing temperatures
IDEX	Index
IDRUN	Alphanumeric identifier for input operating conditions
IJK	Index
IK	Index
IMIX	Index, =1 to calculate performance for mixture of hydrogen and carbon dioxide =0 to calculate performance for pure hydrogen or pure helium
IOUT	Index used as on-off switch for portion of output (that which goes into Tables VII and VIII) 1-on, 0-off
IP	Index used to control printout
IPCV	Index: =0 makes first pass through calculations using uniform pressure in calculating flow rates. Then, make second pass through calculations using pressure array, FIK, (created in first pass) in calculating flow rates. = 1 means eliminate second pass.
IPLOT	Counter used in storing data for plotting
IPRINT	Index used to control printout
IPRNTO	Index used to control printout

IPRNT2	Index used to control printout
IPUMP	Index: =1 means pumping loss due to piston cylinder gap is included =0 means pumping loss not included
IP1	Index
IRE	Index
IREV	Index
ISCD	Index; =1 for separate connecting duct volumes =0 to lump connecting duct volumes with adjacent control volumes
ISIMP	Index
ISTART	Index
ITER	Counts total numer of iterations (time increments) since beginning of run
ITMPS	Index: =1 to print temperature arrays at each time increment (for check out) =0 don't print temperature arrays at each time increment (normally=0)
ITPCYC	Number of iterations (time increments) per cycle
ITR	Counts iterations (time increments) since beginning of cycle
ITRM1	ITR-1
IVAR	Number of iterations in 5 sec
J	Index
JCYCLE	Index, counts number of cycles
JI	Index
JIP	Index: >0 for short form printout in stored dataset =0 long form printout
JIP1	Index
JJ	Index
JM	Index
JN	Index
K	Index
KK	Index
KI	Index
KIDEX	Index used in updating cooler tube temperature
KJK	Index
KTRIG	Index used in updating cooler tube temperature

KTYPE	Index, specifies type of pressure drop calculation to be made
KWRITE	Index
L	Index
M	Index
MAPLOT	Index: =1 means store data for plotting =0 means don't store data for plotting
MWGAS	Index: =2 for hydrogen working gas =4 use helium working gas
N	Index
NA	Index
NC	Number of cooler control volumes
NCL	Index number of last (nearest the compression space) cooler control volume
NCLP1	NCL+1
NCOND	Index used to prevent the conduction subroutine from being called more than once per cycle
NCS	Index number of compression space control volume
NCV	Total number of control volumes
NCVM1	NCV-1
NCVP1	NCV+1
NCVP2	NCV+2
NCVP3	NCV+3
NCVP4	NCV+4
NC1	Index number of first (nearest regenerator) cooler control volume
NC1M1	NC1-1
NC1P1	NC1+1
NES	Index number of expansion space control volume
NH	Number of heater control volumes
NHC	Index number of center heater control volume if there are an odd number of heater control volumes (=NH1 + (NH-1)/2)
NHL	Index number of last heater control volume
NHLP1	NHL+1
NH1	Index number of first (nearest expansion space) heater control volume
NH1M1	NH1-1
NH1P1	NH1+1
NITPC	Number of time increments per cycle

NOCYC	Number of engine cycles
NOEND	Number of cycle at which regenerator matrix temperature convergence procedure is to be turned off
NPASS	Index automatically set by program on basis of input value of index, IPCV. If IPCV=0, then NPASS is set =2 to get two passes through calculations. If IPCV=1, then NPASS is set =1 to get one pass only through calculations.
NPLOTS	Number of variables to be plotted
NR	Number of regenerator control volumes
NRC	Index number of center regenerator control volume
NRCM1	NRC-1
NRCP1	NRC+1
NRL	Index number of last regenerator control volume
NRLM2	NRL-2
NRLP1	NRL+1
NR1	Index number of first (nearest heater) regenerator control volume
NR1M1	NR1-1
NR1M2	NR1-2
NR1M3	NR1-3
NSTRT	Number of cycle at which regenerator matrix temperature convergence procedure is turned on
OLDTIM	Time at end of cycle, to use in calculating period, sec
OMEGA	Engine frequency, Hz
P	Pressure at center of regenerator, lbf/in^2 (MPa)
PC	Pressure in compression space, lbf/in^2 (MPa)
PCDUC	Pressure in compression space when only cooler pressure drop is accounted for, lbf/in^2 (MPa)
PCDUE	Pressure in compression space when only end effects pressure drop is accounted for, lbf/in^2 (MPa)
PCDUR	Pressure in compression space when only regenerator pressure drop is accounted for, lbf/in^2 (MPa)
PCMAX	Maximum compression space pressure, lbf/in^2 (MPa)
PCMIN	Minimum compression space pressure, lbf/in^2 (MPa)
PCMNP	Minimum compression space pressure, Mpa

PCMP	Alternate storage location for compression space pressure, lbf/in^2 (MPa)
PCMXP	Maximum compression space pressure, Mpa
PCSUM	Summation of compression space pressures used in calculating time averaged compression space pressure, lbf/in^2 (MPa)
PCV	Array containing control volume pressures, lbf/in^2 (MPa)
PD	Desired mean pressure level, lbf/in^2 (MPa)
PDFP4	Engine pressure drop loss, ft-lbf/cycle (J/cycle)
PDHP4	Engine pressure drop loss, hp (kW)
PDKW4	Engine pressure drop loss, kW
PE	Expansion space pressure, lbf/in^2 (MPa)
PEALT	Expansion space pressure when pressure drop is calculated relative to pressure in compression space (instead of pressure at center of regenerator), lbf/in^2 (MPa)
PEDUE	Expansion space pressure when only end effects pressure drop is considered, lbf/in^2 (MPa)
PEDUH	Expansion space pressure when only heater pressure drop is considered, lbf/in^2 (MPa)
PEDUR	Expansion space pressure when only regenerator pressure drop is considered, lbf/in^2 (MPa)
PEMAX	Maximum expansion space pressure, lbf/in^2 (MPa)
PEMIN	Minimum expansion space pressure, lbf/in^2 (MPa)
PEMNMP	Minimum expansion space pressure, MPa
PEMXMP	Maximum expansion space pressure, MPa
PERREB	Percent error, engine energy balance
PESUM	Summation of expansion space pressures used in calculating time averaged expansion space pressure, lbf/in^2 (MPa)
PEXP	Alternate storage location for expansion space pressure, lbf/in^2 (MPa)
PHASE	Angle by which the compression volume lags the expansion volume, deg
PI	Constant=3.14159265
PIN	Pressure at control volume inlet, lbf/in^2 (MPa)
PIO2	PI/2
PIO4	PI/4
PLOT	Array in which variables to be plotted are stored
PMEAN	Alternate storage location for mean pressure, lbf/in^2 (MPa)

POLD	Value of reference pressure at time increment previous to current time, lbf/in^2 (MPa)
POUT	Pressure out of control volume, lbf/in^2 (MPa)
PR	Prandtl number, dimensionless in subroutine HEATX--or-- pressure ratio (POUT/PIN) in subroutine XDEL
PRATAV	Pressure ratio--(PEMAX+PCMAX)/(PEMIN+PCMIN)
PRATC	Pressure ratio--PCMAX/PCMIN
PRATE	Pressure ratio--PEMAX/PEMIN
PREGER	Percent error in regenerator energy balance
PRH2O	Prandtl number for cooling water flow
PRIN	Pressure at hot end of regenerator, lbf/in^2 (MPa)
PROSTY	Regenerator matrix porosity
PROUT	Pressure at cold end of regenerator, lbf/in^2 (MPa)
PRSUM	Summation of pressures at center of regenerator used to calculate time averaged working space pressures, lbf/in^2 (MPa)
PS	Array of variables equivalent to pressures in COMMON /PSET/
PSI	Crank angle, radians in subroutine ROMBC--or--conversion constant, 1/144=0.006945 ft^2/in^2 in subroutine XDEL
PSIDEG	Crank angle, deg
PSIOLD	Value of crank angle at time increment before current time, rad
PWRFP1	Engine indicated power per cylinder, ft-lbf/cycle (J/cycle)
PWRFP4	Engine indicated power, ft-lbf/cycle (J/cycle)
PWRHP	Engine indicated power per cylinder, hp (kW)
PWRHP4	Engine indicated power, hp (kW)
PWRKW1	Engine indicated power per cylinder, kW
PWRKW4	Engine indicated power, kW
PXIN	Pressure, lbf/in^2 (MPa)
Q	Array of control volume heat transfers from gas to metal, Btu/sec (W)
QADD	Control volume heat transfer between gas and metal for one time increment, ft-lbf (J)
QAPGAP	Appendix gap loss per cylinder, ft-lbf/cycle (J/cycle)
QBTUPS	Rate of heat out through cooling water per cylinder, Btu/sec (W)
QCAN	Rate of heat conduction through external insulation container, Btu/sec (not used in P40-model)
QCGP	Rate of heat transfer between wall and cold appendix gap, Btu/sec (W)
QCGPS	Appendix gap loss, cold end of piston, ft-lbf/cycle (J/cycle)

QCLEXF	Heat out through cooling water per cylinder, ft-lbf/cycle (J/cycle)
QCLOUT	Heat out through cooling water, excluding heat generated by mechanical friction, ft-lbf/cycle (J/cycle)
QCLRSV	Alternate storage location for net heat out through cooler per cycle, ft-lbf/cycle (J/cycle)
QCNDCL	Heat conducted through cyclinder housing, ft-lbf/cycle (J/cycle)
QCNDCN	Heat conducted through insulation container, ft-lbf/cycle (J/cycle)
QCNDD	Heat conducted through piston walls, ft-lbf/cycle (J/cycle)
QCNDRI	Heat conducted into hot end of regenerator housing, ft-lbf/cycle (J/cycle)
QCNDRO	Heat conducted out of cold end of regenerator housing, ft-lbf/cycle (J/cycle)
QCNDTI	Heat into engine via conduction (includes shuttle) per cylinder, ft-lbf/cycle (J/cycle)
QCNDTO	Heat out of engine via conduction (includes shuttle) per cylinder, ft-lbf/cycle (J/cycle)
QCOLN	Cooler heat transfer from metal to gas for one time increment, ft-lbf (J)
QCOLP	Cooler heat transfer from gas to metal for one time increment, ft-lbf (J)
QCOM	Compression space heat transfer for one time increment, ft-lbf (J)
QCOMP	Net heat transferred from gas to metal in compression space, ft-lbf/cycle (J/cycle)
QCOMPN	Heat transferred from metal to gas in compression space, ft-lbf/cycle (J/cycle)
QCOMPP	Heat transferred from gas to metal in compression space, ft-lbf/cycle (J/cycle)
QCONDD	Rate of heat conduction through piston wall, Btu/sec (W)
QCOOL	Net cooler heat transfer for one time increment, ft-lbf (J)
QCOOLN	Heat transferred from gas to metal in cooler, ft-lbf/cycle (J/cycle)
QCOOLP	Heat transferred from metal to gas in cooler, ft-lbf/cycle (J/cycle)
QCOOLR	Net heat transferred from gas to metal in cooler, ft-lbf/cycle (J/cycle)
QCREG	Rate of heat transfer through regenerator housing, Btu/sec (W)
QCRIN	Heat conduction rate into hot end of regenerator housing, btu/sec (W)

QCROUT Heat conduction rate out of cold end of regenerator housing, Btu/sec (W)

QCYL Rate of heat transfer through cylinder housing, Btu/sec (W)

QCYL1 Heat conduction rate from hot end to middle of cylinder housing, Btu/sec (W)

QCYL2 Heat conduction rate from middle to cold end of regenerator housing, Btu/sec (W)

QEIN Net heat rate to engine per cylinder, ft-lbf/cycle (J/cycle)

QEOUT Net heat from engine per cylinder (includes heat out via cooling water plus auxiliary losses), ft-lbf/cycle (J/cycle)

QEX Expansion space heat transfer for one time increment, ft-lbf (J)

QEXP Net heat transferred from gas to metal in expansion space, ft-lbf/cycle (J/cycle)

QEXPN Heat transferred from metal to gas in expansion space, ft-lbf/cycle (J/cycle)

QEXPP Heat transferred from gas to metal in expansion space, ft-lbf/cycle J/cycle)

QHEAT Heater heat transfer for one time increment, ft-lbf (J)

QHEATN Heat transferred from metal to gas in heater, ft-lbf/cycle (J/cycle)

QHEATP Heat transferred from gas to metal in heater, ft-lbf/cycle (J/cycle)

QHEATR Net heat transferred from gas to metal in heater, ft-lbf/cycle (J/cycle)

QHETN Heater heat transfer from metal to gas for one time increment, ft-lbf (J)

QHETP Heater heat transfer from gas to metal for one time increment, ft-lbf (J)

QHGP Rate of heat transfer between cylinder wall and hot appendix gas, Btu/sec (W)

QHGPS Appendix gap loss, hot end of piston, ft-lbf/cycle (J/cycle)

QIN Heat into engine per cylinder (accounts for heating effect of pressure drop loss in hot end of engine), ft-lbf/cycle (J/cycle)

QINB Heat into engine via heater and expansion space per cylinder, ft-lbf/cycle (J/cycle)

QINFP4 Heat into engine (accounts for heating effect of pressure drop loss in hot end of engine), ft-lbf/cycle (J/cycle)

QINHP4	Heat into engine (accounts for heating effect of pressure drop loss in hot end of engine), hp (kW)
QINKW1	Heat into engine per cylinder (accounts for heating effect of pressure drop loss in hot end of engine), kW
QINKW4	Heat into engine (accounts for heating effect of pressure drop loss in hot end of engine), kW
QOA	Array of control volume heat transfer rates per unit area, Btu/sec-in^2 or Btu/sec-ft^2 (W/cm^2)
QOAMX	Array of control volume maximum heat transfer rates per unit area, Btu/sec-ft^2 (W/cm^2)
QOAAVG	Array of control volume average heat transfer rates per unit area, Btu/sec-ft^2
QOAMX	Array of control volume maximum heat transfer rates per unit area, Btu/sec-ft^2 (W/cm^2)
QOTFP4	Heat out through cooling water for engine, ft-lbf/cycle (J/cycle)
QOTHP1	Heat out through cooling water per cylinder, hp (kW)
QOTHP4	Heat out through cooling water for engine, hp (kW)
QOTKW1	Heat out through cooling water per cylinder, kW
QINKW4	Heat out through cooling water for engine, kW
QOUT	Net heat flow to coolant (larger than heat flow to cooler by mechanical losses), ft-lbf/cycle (J/cycle)
QOUTB	Heat out through cooler and compression space per cylinder, ft-lbf/cycle (J/cycle)
QRAD	Rate of radiation heat transfer in expansion space, Btu/ft^2-hr (W/cm^2)
QREGE	Regenerator heat transfer for one time increment, ft-lbf (J)
QREGEN	Net heat flow from gas to metal in regenerator, ft-lbf/cycle (J/cycle) (should be close to zero for convergent solution)
QREGN	Heat flow from metal to gas in regenerator, ft-lbf/cycle (J/cycle)
QREGP	Heat flow from gas to metal in regenerator, ft-lbf/cycle (J/cycle)
QRGN	Regenerator heat transfer from metal to gas for one time increment, ft-lbf (J)
QRGP	Regenerator heat transfer from gas to metal for one time increment, ft-lbf (J)
QSHTL	Piston shuttle loss, ft-lbf/cycle (J/cycle)
QSHTTL	Rate of heat loss via piston shuttle, Btu/sec (W)

R	Gas constant, in-lbf/lbm-°R (J/kg-K)
RC	Array of dimensionless coefficients used in regenerator matrix temperature convergence method
RCDV	Volume of regenerator-cooler connecting ducts per cylinder, in^3 (cm^3)
RCRANK	Crank radius, in (cm)
RDEDV	Regenerator dead volume per cylinder, in^3 (cm^3)
RE	Reynolds number
REALGS	=1 for real gas equation of state, =0 for ideal gas equation of state
RECD1	Reynolds number in expansion space-heater connecting duct (based on average of inlet and outlet flow rates)
RECD2	Reynolds number in heater-regenerator connecting duct
RECD3	Reynolds number in regenerator-cooler connecting duct
RECD4	Reynolds number in cooler-compression space connecting duct
RECMP	Reynolds number at entrance of compression space
REEXP	Reynolds number at exit of expansion space
REFF1	Measure of regenerator effectiveness (ENFRTH/ENFHTR)
REFF2	Measure of regenerator effectiveness (ENFCTR/ENFRTC)
REGDMB	Regenerator housing distance between middle and bottom temperature measurement locations, in (cm)
REGDTM	Regenerator housing distance between top and middle temperature measurement locations, in (cm)
REGID	Regenerator inside diameter (matrix diameter), in (cm)
REGIR	Regenerator housing inside radius, in (cm)
REGL	Regenerator matrix length, in (cm)
REGORB	Regenerator housing outside radius, bottom, in (cm)
REGORM	Regenerator housing outside radius, middle, in (cm)
REGORT	Regenerator housing outside radius, top, in (cm)
REGPCN	Number of regenerators per cylinder
REH2O	Reynolds number for cooling water flow rate
REIC	Reynolds number in cooler control volume nearest the regenerator
REIH	Reynolds number in heater control volume nearest the expansion space
REIR	Reynolds number in regenerator control volume nearest the heater
REOC	Reynolds number in cooler control volume nearest the compression space
REOH	Reynolds number in heater control volume nearest the regenerator
REOR	Reynolds number in regenerator control volume nearest the cooler

RETABL	Array of Reynolds number values corresponding to values of the heat transfer correlation in array HTABL
REYNO	Array of working gas control volume Reynolds numbers
RGAREA	Regenerator cross-sectional flow area with no matrix, in^2 (cm^2)
RHCFAC	Regenerator heat transfer coefficient multiplier
RHCPCV	Regenerator matrix heat capacity per control volume (per cylinder) Btu/°R (J/K)
RHOH2O	Density of water, lbm/ft^3 (gm/cm^3)
RH2O	Resistance to heat flow from cooler tube to cooling water, sec-°R/Btu (K/W)
RMDEN	Regenerator matrix metal density, lbm/in^3 (gm/cm^3)
RO	Working gas density, lbm/ft^3 (gm/cm^3)
RODL	Connecting rod length, in (cm)
ROX	Working gas density, lbm/in^3 (gm/cm^3)
RP	Gas constant, btu/lbm-°R (J/kg-K)
RPM	Engine speed, rpm (Hz)
RPMF	Speed for auxiliary requirement calculation (assumes design speed of 4000 rpm), rpm (Hz)
RPMFN	Speed for auxiliary loss requirements correction, thousands of rpm
RTUBE	Cooler tube wall resistance, sec-°R/Btu (°K/W)
RWIRED	Regenerator matrix wire diameter, in (cm)
SAVET	Save time required for first nocyc cycles before resetting time=0
SET	Array of variables equivalent to work variables in COMMON /RESET/
SRULE	Function used in performing Simpson rule integration
STORE	Array used to store cycle quantities to allow calculation of averages over five cylcles, various dimensions
STROKE	Piston stroke, in (cm)
SUM	Summation over gas control volumes of (pressure * volume)/ (gas constant * temperature), dimensionless
SUMDEN	Array used in calculating time weighted average of difference between regenerator matrix and gas temperatures, lbm (kg)
SUMNUM	Array used in calculating time weighted average of difference between regenerator matrix and gas temperatures, lbm-°R (kg-K)
SUMV	Summation of (control volumes * array of pressure ratio factors), in^3 (cm^3)

SUMWF Summation of (control volume gas inventories * pressure ratio factors), lbm (kg)

SUMWT Summation of (control volume gas inventories * control volume gas temperatures), lbm-deg R (Kg-°K)

T1 Expansion space gas temperature, °R (K)

T2 Compression space gas temperature, °R (K)

TCAN Array of external insulation container temperatures for conduction calculations, °R (K)

TCAVG Average cooler tube temperature, °R in subroutine CYCL--or--temperature used in heat conduction calculation, °R in subroutine CNDCT (K)

TCAVG1 Temperature used in heat conduction calculation, °R (K)

TCAVG2 Temperature used in heat conduction calculation, °R (K)

TCAVGC Average cooler tube temperature, °C

TCAVGF Average cooler tube temperature, °F (°C)

TCAVGK Average cooler tube temperature, °K

TCGP Temperature used in appendix gap loss calculation at cold end of piston, °R (K)

TCGPI Temperature of gas crossing interface between cold appendix gap and compression space, °R (K)

TCLRM Inside wall cooler tube temperature, °R (K)

TCLRMO Alternate storage location for TCLRM, °R (K)

TCYL Array of cylinder housing temperatures used in conduction calculations °R (K)

TG Array of control volume interface gas temperatures, °R (K)

TGA Array of control volume gas temperatures, °R (K)

TGACYC Array of time averaged control volume gas temperatures, °R (K)

TGAO Alternate storage array for array TGA, °R (K)

TGAVG Average temperature of piston walls, °R (K)

TGCMPA Time averaged compression space gas temperature, °R (K)

TGCYC Array of time averaged control volume interface gas temperatures, °R (K)

TGEXPA Time averaged expansion space gas temperature, °R (K)

THAVG Average heater tube temperature, °R (K)

THAVGC Average heater tube temperature, °C

THAVGF Average heater tube temperature, °F (°C)

THAVGK	Average heater tube temperature, °K
THCNDG	Average thermal conductivity of gas in gap between piston and cylinder wall, Btu/in-sec-°R (W/cm-K)
THCND1	Thermal conductivity, Btu/in-sec-°R (W/cm-K)
THCND2	Thermal conductivity, Btu/in-sec-°R (W/cm-K)
THCOND	Thermal conductivity, Btu/in-sec-°R (W/cm-K)
THGP	Temperature used in appendix gap loss calculation, hot end of piston, °R (K)
THGPI	Temperature of gas crossing interface between hot appendix gap and expansion space, °R (K)
TH2OAV	Average cooling water temperature, °R (K)
TH2OIN	Cooling water inlet temperature, °R (K)
TH2ONC	Cooling water inlet temperature, °C
TH2ONF	Cooling water inlet temperature, °F (C)
TH2ONK	Cooling water inlet temperature, K
TIME	Time since beginning of first engine cycle, sec
TM	Array of control volume wall temperatures, °R (K)
TMA	Array of control volume wall temperatures, °R (K)
TMAO	Alternate array for array TMA, °R (K)
TMCYC	Array of time averaged wall temperatures, °R (K) (current model lets only regenerator wall temperatures vary over the cycle)
TMEXP	Expansion space wall temperature, °R (K)
TMHBR	Back row heater tube outside wall temperature, °R (K)
TMHFR	Front row heater tube outside wall temperature, °R (K)
TMIX	Array of control volume gas temperatures, after mixing and before heat transfer, °R (K)
TQOFP4	Total heat out of engine (heat out through cooling water plus auxiliary loss), ft-lbf/cycle (J/cycle)
TQOHP4	Total heat out of engine (heat out through cooling water plus auxiliary loss), hp (kW)
TQOKW4	Total heat out of engine (heat out through cooling water plus auxiliary loss), kW
TR	Temperature ratio (out/in)
TRAVG1	Average temperature, top half of regenerator housing, °R (K)
TRAVG2	Average temperature, bottom half of regenerator housing, °R (K)
TRIN	Gas temperature at hot end of regenerator, °R (K)

TROUT	Gas temperature at cold end of regenerator, °R (K)
TRO	Regenerator housing temperature, hot end, used in conduction calculation, °R (K)
TR1	Regenerator housing temperature, middle, used in conduction calculation, °R (K)
TR2	Regenerator housing temperature, cold end, used in conduction calculation, °R (K)
TWOPI	Constant, 2 * PI
UTOTAL	Internal energy content of working space gas control volumes, ft-lbf (J)
V	Array of working space gas control volumes, in^3/cylinder (cm^3/cylinder)
VAR	Array of variables equivalent to the variable in COMMON /CYC/
VCAPGP	Appendix gap volume at cold end of piston, in^3 (cm^3)
VCLC	Net compression space clearance volume (includes cold appendix volume), in^3 (cm^3)
VCLE	Net expansion space clearance volume (includes hot appendix gap volume), in^3 (cm^3)
VCO2	Volume fraction of carbon dioxide
VEL	Gas flow velocity, ft/sec (cm/sec)
VELHD	Velocity head, lbf/ft^2 (N/cm^2)
VHAPGP	Hot appendix gap volume, in^3
VH2	Volume fraction of hydrogen
VIS	Array of control volume gas viscosities, lbm/in-sec
VISC	Viscosity, lbm/ft-sec (kg/cm-sec)
VISCO2	Viscosity of carbon dioxide, lbm/in-sec (kg/cm-sec)
VISH2	Viscosity of hydrogen, lbm/in-sec (kg/cm-sec)
VISH2O	Average cooling water viscosity, lbm/ft-sec (kg/cm-sec)
VISX	Viscosity, lbm/in-sec (kg/cm-sec)
VO	Alternative storage array for working space gas control volumes, in^3 (cm^3)
VOVRT	Summation over the array of gas control volumes of--volume/(temperature*pressure ratio (i.e. FIK)), in^4-lbf/lbm-°R (cm^4-N/kg-K)
VR	Velocity ratio (out/in)
VTOTL	Total working space volume, in^3 (cm^3)

VTOTLO Alternate storage location for total working space volume, in^3 (cm^3)

W Total working space gas inventory per cylinder, lbm (kg)

WALT Total work per cycle if pressure drops are calculated relative to compression space pressure, ft-lbf/cycle (J/cycle)

WALTO Alternate storage location for WALT, ft-lbf/cycle

WCDUCO, WCDUC1, WCDUC2 Compression space work per time increment if only cooler pressure drop is considered, three consecutive time increments, ft-lbf (J)

WCDUEO, WCDUE1, WCDUE2 Compression space work per time increment if only end effects pressure drop is considered, three consecutive time increments, ft-lbf (J)

WCDURO, WCDUR1, WCDUR2 Compression space works per time increment if only pressure drop considered is that in the cold half of the regenerator, three consecutive time increments, ft-lbf (J)

WCF Correction factor for gas inventory to get desired mean pressure, dimensionless

WCMPN Negative compression space work per cycle, ft-lbf/cycle (J/cycle)

WCMPP Positive compression space work per cycle, ft-lbf/cycle (J/cycle)

WCPCO, WCPC1, WCPC2 Compression space work per time increment, three consecutive time increments, ft-lbf (J)

WCPO, WCP1, WCP2 Compression space work per time increment assuming no pressure drop, three consecutive time increments, ft-lbf (J)

WDTGA (change in control volume gas temperature * control volume gas inventory), °R-lbm (K-kg)

WFCTR (dimensionless function of control volume heat transfer * control volume gas inventory), lbm (kg)

WEALTO, WEALT1, WEALT2 Expansion space work per time increment if pressure drop is calculated relative to compression space pressure, three consecutive time increments, ft-lbf (J)

WEDUEO, WEDUE1, WEDUE2 Expansion space work per time increment if only end effects pressure drop is considered, three consecutive time increments, ft-lbf (J)

WEDUHO, WEDUH1, WEDUH2 Expansion space work per time increment if only heater pressure drop is considered, three consecutive time increments, ft-lbf (J)

WEDURO, WEDUR1, WEDUR2 Expansion space work per time increment is only regenerator pressure drop is considered, three consecutive time increments, ft-lbf (J)

WEPEO, WEPE1, WEPE2 Expansion space work per time increment, three consecutive time increments, ft-lbf (J)

WEPO, WEP1, WEP2 Expansion space work per time increment assuming no pressure drop, three consecutive time increments, ft-lbf (J)

WEXPN Negative expansion space work per cycle, ft-lbf/cycle (J/cycle)

WEXPP Positive expansion space work per cycle, ft-lbf/cycle (J/cycle)

WG Array of control volume gas inventories, lbm (kg)

WGCGP Cold appendix gap inventory, lbm (kg)

WGCGPO Cold appendix gap inventory at time increment previous to current value, lbm (kg)

WGHGP Hot appendix gap inventory, lbm (kg)

WGHGPO Hot appendix gap inventory at time increment previous to current value, lbm (kg)

WGOLD Array of control volume gas inventories, at one time increment before current value, lbm (kg)

WINT Work integral function

WLALT Work loss at expansion space (due to pressure drop) when pressure drop is calculated relative to reference pressure in compression space, ft-lbf cycle (J/cycle)

WLALTO Alternate storage location for WLALT

WLCMC Work loss at compression space due to cooler pressure drop, ft-lbf/cycle (J/cycle)

WLCME Work loss at compression space due to end effects pressure drop, ft-lbf/cycle (J/cycle)

WLCMR Work loss at compression space due to regenerator pressure drop, ft-lbf/cycle (J/cycle)

WLEALT Work loss at expansion space due to pressure drop when the pressure drop is calculated relative to the compression space pressure, ft-lbf/cycle (J/cycle)

WLEXE Work loss at expansion space due to end effects pressure drop, ft-lbf/cycle (J/cycle)

WLEXH Work loss at expansion due heater pressure drop, ft-lbf/cycle (J/cycle)

WLEXR	Work loss at expansion due to regenerator pressure drop, ft-lbf/cycle (J/cycle)
WRKBAS	Indicated work + pressure drop work loss, per cylinder, ft-lbf/cycle (J/cycle)
WRKCMP	Compression space work per cycle, ft-lbf/cycle (J/cycle)
WRKEXP	Expansion space work per cycle, ft-lbf/cycle (J/cycle)
WRKLC	Work loss at compression space due to cooler pressure drop, per cylinder, ft-lbf/cycle (J/cycle)
WRKLCM	Work loss at compression space due to pressure drop, ft-lbf/cycle (J/cycle)
WRKLCO	Alternate storage location for WRKLC, ft-lbf/cycle, (J/cycle)
WRKLE	Total work loss due to end effects pressure drop, ft-lbf/cycle (J/cycle)
WRKLEO	Alternate storage location for WRKLE, ft-lbf/cycle (J/cycle)
WRKLEX	Work loss at expansion space due to pressure drop, ft-lbf/cycle (J/cycle)
WRKLH	Work loss at expansion space per cylinder due to heater pressure drop, ft-lbf/cycle (J/cycle)
WRKLHO	Alternate storage location for WRKLH, ft-lbf/cycle (J/cycle)
WRKLR	Total work loss due to regenerator pressure drop, ft-lbf/cycle (J/cycle)
WRKLRO	Alternate storage location for WRKLR, ft-lbf/cycle (J/cycle)
WRKLT	Total work loss due to pressure drop, ft-lbf/cycle (J/cycle)
WRKLTO	Alternate storage location for WRKLT, ft-lbf/cycle (J/cycle)
WRKTOT	Indicated work per cycle, ft-lbf/cycle (J/cycle)
WTPCO, WTPC1, WTPC2	Total work per time increment when pressure drop is calculated relative to compression space pressure, ft-lbf/cycle (J/cycle)
WO	Array of variables equivalent to works in COMMON /TIMEO/
W1	Array of variables equivalent to works in COMMON /TIME1/
W2	Array of variables equivalent to works in COMMON /TIME2/
X	Array (two dim.) of piston positions, in (cm)
XCO2	Mass fraction of carbon dioxide
XCPA	Specific heat at constant pressure, Btu/lbm-°R (J/kg-K)
XCV	Specific heat at constant volume, Btu/lbm-°R (J/kg-k)
XGAM	Ratio of specific heats (CP/CV)

XH2	Mass fraction of hydrogen
XL	Array of control volume flow lengths, in (cm)
XLG	Length, ft (cm)
XLGTH	Length, in (cm)
XLO	Alternate storage array for XL, in (cm)
XMAO	Estimate of outlet Mach number
XMA1	Inlet Mach number
XMA2	Outlet Mach number
ZERO	Constant =0.0
ZMCO2	Molecular wt. of carbon dioxide
ZMH2	Molecular wt. of hydrogen
ZMMIX	Molecular weight of mixture of hydrogen and carbon dioxide

APPENDIX G: COMPARISON OF PREDICTIONS WITH TEST DATA

Predicted P-40 engine brake power and efficiences are compared with the results of engine tests made at Lewis Research Center in figure 15. The tests were made with auxiliaries powered by the engine. The efficiencies shown are overall efficiencies. The efficiency predicted by the computer program does not account for the combustor efficiency. Thus it was necessary to use an assumed combustor efficiency to adjust the predictions of the computer program. The combustor efficiencies calculated from the Lewis P-40 test data were all about 90 percent for the test points shown. When the predicted efficiencies were multiplied by 0.90, the upper predicted efficiency curve was obtained . However, information obtained from United Stirling suggests the P-40 combustor efficiency may be closer to 80 percent for the range of operation shown. When the predicted efficiencies were multiplied by 0.80, the lower predicted efficiency curve was obtained.

The regenerator effectiveness (average of REFF1 and REFF2 - defined in the symbols list) was about 0.996 for the predictions of figure 15. When the computer program was modified to yield a regenerator effectiveness of about 0.990 (by multiplying DTGASL by 0.96, in subroutine HEATX) the predictions were as shown in figure 16.

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TABLE I. – EFFECT OF CHANGING THE NUMBER OF CONTROL VOLUMES IN THE HEAT EXCHANGERS

CONTROL VOLUME CHANGE	CHANGE IN TOTAL NO. OF CONTROL VOLUMES	EFFECT ON ENGINE POWER
REGENERATOR, 5 → 7	17 → 19	≃ + 0.5 kW
HEATER, 3 → 5	17 → 19	≃ + 0.25 kW
COOLER, 3 – 5	17 → 19	≃ + 0.25 kW
REGENERATOR, 5 → 7 HEATER, 3 → 5 COOLER, 3 → 5	17 → 23	≃ + 1.0 kW

TABLE II. - INPUT DATA--ENGINE PARAMETERS

```
&ENGINE EID=8HP40      ,ETYPE=1., DISPD=2.165,    DISPRD=.4724,  DSPGAP=.01575,
   DSPHGT=3.53,    RODL=3.937,     RCRANK=.7874,  E=0.0,         PHASE=90.,
   HTBOD=.1772,    HTBID=.1181,    HTBPCN=18.,    HTBL=11.05,    EHTBL=9.913,
                   REGPCN=2.,      REGID=2.244,   REGL=1.535,    RWIRED=1.969E-3,
   PROSTY=0.58,                    RMDEN=0.282,   CPM=0.11,      CTBOD=5.906E-2,
   CTBID=3.937E-2,CTBPCN=384.,     CTBL=3.150,    ECTBL=2.646,
   CNDSS=2.778E-3,CPH2O=1.0,       RHOH2O=62.4,   AEFH2O=5.00,   EXPSCL=.1452,
   EXPHDV=.2691,   HRDV=1.017,     RCDV=.3112,    CCMPDV=1.843,  CMPSCL=.1379,
   CYLORT=1.36,    CYLORM=1.31,    CYLORB=1.25,   CYLDTM=0.787,  CYLDMB=0.787,
   DSPWTH=0.075,   REGORT=1.42,    REGORM=1.37,   REGORB=1.30,   REGDTM=0.594,
   REGDMB=0.594,   STROKE=1.575,   CANOR=0.0,     CANIR=0.0,     CONDTB=0.0,
   DFREQ=66.67,     DFLOSS=17.165, DALOSS=10.06
&END
```

TABLE III: SYMBOL DEFINITIONS FOR
ENGINE PARAMETER INPUT DATA
(NAMELIST /ENGINE/)

SYMBOL	DEFINITION
EID	Alphanumeric engine identifier
ETYPE	Numeric engine identifier
DISPD	Piston diameter, in (cm)
DISPRD	Piston rod diameter, in (cm)
DSPGAP	Piston-cylinder gap, in (cm)
DSPHGT	Displacer height, in (cm)
RODL	Connecting rod length, in (cm)
RCRANK	Crank radius, in (cm)
E	Eccentricity (not used)
PHASE	Angle by which compression volume lags expansion volume, deg
HTBOD	Heater tube outside diameter, in (cm)
HTBID	Heater tube inside diameter, in (cm)
HTBPCN	Number of heater tubes per cylinder
HTBL	Heater tube length, in (cm)
EHTBL	Length of heater tube effective in heat transfer, in (cm)
REGPCN	Number of regenerators per cylinder
REGID	Regenerator inside diameter, in (cm)
REGL	Regenerator matrix length, in (cm)
RWIRED	Regenerator matrix wire diameter, in (cm)
PROSTY	Regenerator matrix porosity
RMDEN	Regenerator matrix metal density, $\frac{LB_M}{in^3}\left(\frac{gM}{cm^3}\right)$
CPM	Regenerator matrix specific heat, $\frac{Btu}{LB_M - {}^\circ R}\left(\frac{JOULES}{gM - K}\right)$
CTBOD	Cooler tube outside diameter, in (cm)
CTBID	Cooler tube inside diameter, in (cm)
CTBPCN	Number of cooler tubes per cylinder
CTBL	Cooler tube length, in (cm)
ECTBL	Length of cooler tube effective in heat transfer, in (cm)
CNDSS	Cooler tube thermal conductivity,

$$\frac{\text{Btu}}{\text{ft - sec - }^\circ\text{R}}\left(\frac{\text{watt}}{\text{cm - k}}\right)$$

CPH2O	Cooling water specific heat, $\frac{\text{Btu}}{\text{lbm - }^\circ\text{R}}\left(\frac{\text{joules}}{\text{gm - k}}\right)$
RHOH2O	Density of water, $\frac{Lb_M}{ft^3}\left(\frac{gm}{cm^3}\right)$
AEFH2O	Effective cooling water flow area per cylinder, in^2 (cm^2)
EXPSCL	Expansion space clearance volume, in^3 (cm^3)
EXPHDV	Expansion space - heater connecting duct volume, in^3 (cm^3)
HRDV	Heater-regenerator connecting duct volume, in^3 (cm^3)
RCDV	Regenerator-cooler connecting duct volume, in^3 (cm^3)
CCMPDV	Cooler-compression space connecting duct volume, in^3 (cm^3)
CMPSCL	Compression space clearance volume, in^3 (cm^3)
CYLORT	Cylinder housing outside radius, top, in (cm)
CYLORM	Cylinder housing outside radius, middle, in (cm)
CYLORB	Cylinder housing outside radius, bottom, in (cm)
CYLDTM	Cylinder housing conduction length, top to middle, in (cm)
CYLDMB	Cylinder housing conduction length, middle to bottom, in (cm)
DSPWTH	Piston wall thickness, in (cm)
REGORT	Regenerator housing outside radius, top, in (cm)
REGORM	Regenerator housing outside radius, middle, in (cm)
REGORB	Regenerator housing outside radius, bottom, in (cm)
REGDTM	Regenerator housing conduction length, top to middle, in (cm)
REGDMB	Regenerator housing conduction length, middle to bottom, in (cm)
STROKE	Piston stroke, in (cm)
CANOR	Insulation container outside radius (not used)

CANIR	Insulation container inside radius (not used)
CONDTB	Insulation container conduction length (not used)
DFREQ	Design engine frequency, Hz (rpm)
DFLOSS	Design mechanical friction loss, hp (kW)
DALOSS	Design auxiliary power requirement, hp (kW)

TABLE IV. - MODEL OPTION SWITCHES AND MULTIPLYING FACTORS,

AND ENGINE OPERATING CONDITIONS

```
&STRLNG REALGS=1.,FACT1=0.4,FACT2=10.0,
NOCYC=25,NSTRT=1,NOEND=20,MWGAS=2,
RHCFAC=1.0,HHCFAC=1.0,CHCFAC=1.0,IPCV=0,FMULT=1.0,FMULTR=1.0,
IMIX=0,VH2=0.99,IPUMP=1,ICOND=0,
IOUT=1,JIP=0,IPRINT=500,ITMPS=0,MAPLOT=1 &END
&INDATA IDRUN=12HREAD #123BR,P=2171.,OMEGA=66.78,TMEXP=1643.,
TMHFR=1672.,TMHBR=1672.,TCYL=1643.,1441.,1239.,TCAN=1191.,999.,TRO=1472.,
TR1=1214.,TR2=956.,GPMH2O=13.63,TH2OIN=580.1 &END
```

TABLE VII. - PARTIAL LISTING OF LONG FORM OF OUTPUT
(PRODUCED WHEN IOUT = 1, JIP = 0)

```
*  RUN IDENTIFICATION **

READ #123BR,


** CALCULATED CONTROL VOLUME AND ENGINE PARAMETERS, AND INPUT DATA **

&EPARAM
HDEDV= 2 1788355858357
RDEDV= 7 0420962338519
CDEDV= 1 4725243637283
DGAPDV= 0 38090003924925
DHO= 2*2 1650, 3*0.11810, 2.2440, 5*0.27190952380952D-02, 0.22440D01, 3*0.39370D-01
2*0 169260D01, 13*0.0
ACSO= 3 6813379069113, 1.8406689534556, 3*0.98589845512928D-01, 0.39549007266381D01
5*0 22938424214501D01, 0.39549007266381D01, 3*0.23373402598861D0, 0.17530335352219D01
0 35060670704439D01, 13*0.0
AHTO= 2*0 0, 3*11.033826006996, 0.0, 5*1035.9469775373, 0.0, 3*20.945228440128
15*0.0
XLO= 0 0, 0 73098424215499D-01, 3*0.36833333333333D01, 0.12857465588833D0
5*0 3070D0, 0.39343591850981D-01, 3*0.1050D01, 0.52566022354121D0, 14*0.0
VO= 0.0, 0.26910, 3*0.72627852861190, 1.0170, 5*1.4084192467704, 0.31120
3*0.49084145457609, 1 8430, 14*0.0
VCLE= 0 52610003924925
VCLC= 0 17599000392493
CLRLOD= 80 010160020320
HTRLOD= 93.564775613887
PCAREA= 3.9549007266381
AP= 3 6813379069113
AR= 0.17527083646743
APMAR= 3 5060670704439
VHAPGP= 0.38090003924925
VCAPGP= 0.38090003924925D-01
THGP= 1373 6666666667
TCGP= 646.40894661755
QHGPS= 0.0
QCGPS= 0.0
IPUMP= 1
ICOND= 0
&END


** INPUT DATA--ENGINE PARAMETERS **

&ENGINE
EID= -0 47377992506120D28
ETYPE= 1.0
DISPD= 2.1650
DISPRD= 0.47240
DSPGAP= 0 15750D-01
DSPHGT= 3.530
RODL= 3.9370
```

```
PCRANK= 0.78740
E= 0 0
PHASE= 90.0
HTBOD= 0 17720
HTBID= 0.11810
HTBPCN= 18.0
HTBL= 11.050
EHTBL= 9.9130
REGPCN= 2.0
REGID= 2.2440
RGL= 1 5350
RWIRED= 0 19690D-02
PROSTY= 0.580
RMDEN= 0 2820
CPM= 0 110
CTBOD= 0.59060D-01
CTBID= 0.39370D-01
CTBPCN= 384.0
CTBL= 3.150
ECTBL= 2.6460
CNDSS= 0 27780D-02
CPH2O= 1.0
RHOH2O= 62.40
AEFH2O= 5.0
EXPSCL= 0.14520
EXPHDV= 0.26910
HRDV= 1.0170
RCDV= 0.31120
CCMPDV= 1 8430
CMPSCL= 0.13790
CYLORT= 1.360
CYLORM= 1.310
CYLORB= 1.250
CYLDTM= 0.7870
CYLDMB= 0 7870
DSPUTH= 0.750D-01
REGORT= 1 420
RECORM= 1.370
RECORB= 1.30
REGDTM= 0.5940
REGDMB= 0.5940
STROKE= 1.5750
CANOR= 0.0
CANIR= 0.0
CONDTB= 0.0
DFREQ= 66.670
DFLOSS= 17.1650
DALOSS= 10.060
&END
```

** INPUT DATA--OPTION SWITCHES AND MULTIPLYING FACTORS **

&STRLNG

```
REALGS= 1.0
FACT1= 0.40
FACT2= 10 0
NOCYC= 25
NSTRT= 1
NOEND= 20
NUGAS= 2
RHCFAC= 1.0
HHCFAC= 1.0
CHCFAC= 1.0
IPCV= 0
FMULT= 1.0
FMULTR= 1.0
IMIX= 0
VH2= 0 990
IPUMP= 1
ICOND= 0
IOUT= 1
JIP= 0
IPPINT= 500
ITMPS= 0
MAPLOT= 1
&END
```

** INPUT DATA--ENGINE OPERATING CONDITIONS **

```
&INDATA
IDRUN= -641351228, 1081864690, -205334165
P= 2635.5934534073
OMEGA= 66.780
TMEXP= 1643 0
TMHFR= 1672.0
TMHBR= 1672.0
TCYL= 1643.0, 1441.0, 1239.0
TCAN= 1191 0, 999.0
TR0= 1472.0
TR1= 1214.0
TR2= 956.0
GPMH2O= 13.630
TH2OIN= 580.10
&END
```

** CYCLE BY CYCLE SUMMARY DATA **

```
 * CYCLE NO.  1 *
   TIME    ANGLE    X(1)   X(2) TRIN       TROUT       T1     T2        PE      PC       PRIN   PROUT     FRIN       FROUT
  0 0000     0.0   0.00   0.71      0.00      0.00    1709.  801.  2635.59 2635.59    0.00      0.00 0.00000 0.00000
  0 0150   360.0   0.00   0.71   1491.76   718.73    1544.  737.  2601.96 2601.96 2601.96 2601.96-0.05553-0.23852
  TG=        1542.   1580.               1645.   1492.              719.    704.              734.    737.
 TGA=   1544.   1543.   1581.   1648.   1643.   1413.    788.    718.    703.    716.    734.    737.
  TM=   1643.   1672.   1672.   1672.   1672.   1413.    789.    646.    646.    646.    646.    696.
```

```
QIN= 497 260 QOUT= 386.541 WRKEXP= 407.993 WRKCMP=-219.057 WRKTOT= 188.937 EFFTOT=   0.380 REFF1=   0.971 REFF2=   0.963
QREGEN=  54.846 PWRHP=  22.940 FREQ=  66.780 WRKLT=   0.000 UTOTAL=     0.000
EN3PM=  6310.710 AVGWSP= 2305.225
QEXPN=  -6.329 QEXPP=   0.021 QHEATN=-490.952 QHEATP=   0.000 QCOOLN=  -0.131 QCOOLP= 333.692 QCOMPN=  -0.570 QCOMPP=   1.786
QREGN=-1805.030 QREGP=1859.876 QCNDRI=  0.000 QCNDRO-  0.000
QCNDCL=   0.000 QCNDD=   0.000 QCNDCN=   0.000 TGEXPA=1498.873 TGCMPA= 736.856 QSHTL=   0.000
QINB = 497 260 WRKBAS = 188.937 WALT = 188.937 QOUTB= 334.777 WRKLEX=   0.000 WRKLCM=  -0.000 WLEXR=   0.000
WLCMR=  -0.000 WLEXE=   0.000 WLCME=  -0.000 WRKLR-   0.000 WRKLH=   0.000 WRKLC=   0.000 WRKLE=   0.000 WLALT=   0.000

* CYCLE NO.  2 *
  TIME    ANGLE   X(1)  X(2) TRIN     TROUT      T1     T2      PE      PC      PRIN   PROUT    FRIN     FROUT
 0 0150   360.0   0.00  0.71  1491.76  718.73    1544.   737.  2601.96 2601.96 2601.96 2601.96-0.05553-0.23852
 0.0299   360.0   0.00  0.71  1489.07  717.78    1571    714.  2583.98 2583.98 2583.98 2583.98-0.05611-0.23860
 TG=        1569.   1603             1658.   1489.               718.    701.            718.    714.
TCA=  1571.   1570.   1603    1663.   1656.   1411.    794.    717.    700.    705.    718.    714.
 TM=  1643.   1672.   1672.   1672.   1672.   1411.    795.    646.    646.    646.    646.    696.
QIN= 421.420 QOUT= 332.610 WRKEXP= 402.730 WRKCMP=-214.445 WRKTOT= 188.285 EFFTOT=   0.447 REFF1=   0.991 REFF2=   0.978
QREGEN=   2.964 PWRHP=  22.861 FREQ=  66.780 WRKLT=   0.000 UTOTAL=     0.000
EN3PM=  6310.710 AVGWSP= 2287.914
QEXPN=  -5.259 QEXPP=   0.003 QHEATN=-416.164 QHEATP=   0.000 QCOOLN=  -0.665 QCOOLP= 283.912 QCOMPN=  -1.268 QCOMPP=   0.722
QREGN=-1824.564 QREGP=1827.528 QCNDRI=  0.000 QCNDRO=  0.000
QCNDCL=   0.000 QCNDD=   0.000 QCNDCN=   0.000 TGEXPA=1515.042 TGCMPA= 696.121 QSHTL=   0.000
QINB = 421 420 WRKBAS = 188.285 WALT = 188.285 QOUTB= 282.702 WRKLEX=   0.000 WRKLCM=  -0.000 WLEXR=   0.000
WLCMR=  -0.000 WLEXE=   0.000 WLCME=  -0.000 WRKLR=   0.000 WRKLH=   0.000 WRKLC=   0.000 WRKLE=   0.000 WLALT=   0.000

* CYCLE NO.  3 *
  TIME    ANGLE   X(1)  X(2) TRIN     TROUT      T1     T2      PE      PC      PRIN   PROUT    FRIN     FROUT
 0 0299   360.0   0.00  0.71  1489.07  717.78    1571.   714.  2583.98 2583.98 2583.98 2583.98-0.05611-0.23860
 0 0449   360.0   0.00  0.71  1486.70  717.41    1579.   703.  2573.47 2573.47 2573.47 2573.47-0.05629-0.23836
 TG=        1578.   1609.            1662.   1487.               717.    700.            710.    703.
TGA=  1579.   1578.   1610.   1668.   1660.   1409.    797.    716.    699.    700.    710.    703.
 TM=  1643.   1672.   1672.   1672.   1672.   1409.    798.    646.    646.    646.    646.    696.
QIN= 406 087 QOUT= 308.442 WRKEXP= 398.882 WRKCMP=-211.725 WRKTOT= 187.157 EFFTOT=   0.461 REFF1=   0.996 REFF2=   0.981
QREGEN= -16.195 PWRHP=  22.724 FREQ=  66.780 WRKLT=   0.000 UTOTAL=     0.000
EN3PM=  6310.710 AVGWSP= 2276 622
QEXPN=  -4.897 QEXPP=   0.074 QHEATN=-402.101 QHEATP=   0.838 QCOOLN=  -1.336 QCOOLP= 259.344 QCOMPN=  -1.697 QCOMPP=   0.389
QREGN=-1825 480 QREGP=1809.285 QCNDRI=  0.000 QCNDRO=  0.000
QCNDCL=   0.000 QCNDD=   0.000 QCNDCN=   0.000 TGEXPA=1526.426 TGCMPA= 680.010 QSHTL=   0.000
QINB = 406.087 WRKBAS = 187.157 WALT = 187.157 QOUTB= 256.701 WRKLEX=   0.000 WRKLCM=  -0.000 WLEXR=   0.000
WLCMR=  -0 000 WLEXE=   0.000 WLCME=  -0.000 WRKLR=   0.000 WRKLH=   0.000 WRKLC=   0.000 WRKLE=   0.000 WLALT=   0.000

* CYCLE NO   4 *
  TIME    ANGLE   X(1)  X(2) TRIN     TROUT      T1     T2      PE      PC      PRIN   PROUT    FRIN     FROUT
 0 0449   360.0   0.00  0.71  1486.70  717.41    1579.   703.  2573.47 2573.47 2573.47 2573.47-0.05629-0.23836

** METAL TEMPERATURES FOR CONDUCTION CALCULATIONS **
&INTEMP
TCYL= 1643 0, 1441.0, 1239.0
TCAN= 1191.0, 999.0
TRO= 1472 0
TR1= 1214.0
TR2= 956.0
&END
```

```
 0.0599   360.0  0.00  0.71  1484.87  716.85   1581.  698.  2562.99 2575.32 2563.88 2569.98-0.05633-0.23828
 TG=         1580.   1611.              1663.   1485.              717.    699.             706.    698.
TCA=   1581.   1580.   1612.   1669.   1661.   1408.    797.    716.    698.    697.    706.    698.
 TM=   1643.   1672.   1672.   1672.   1672.   1408.    799.    646.    646.    646.    646.    696.
QIN= 390.941 QOUT= 308.637 WRKEXP= 376.737 WRKCMP=-215.681 WRKTOT= 161.056 EFFTOT=   0.412 REFF1=   0.997 REFF2=   0.984
QREGEN= -17.064 PWRHP=  19.555 FREQ=  66.780 WRKLT=  25.379 UTOTAL=      0.000
EN3PM=  6310.710 AVGWSP= 2269.566
QEXPN=  -4.793 QEXPP=   0.105 QHEATN=-398.994 QHEATP=   1.619 QCOOLN=  -1.934 QCOOLP= 245.702 QCOMPN=  -1.926 QCOMPP=   0.251
QREGN=-1819.351 QREGP=1802.287 QCNDRI=  5.178 QCNDRO=  5.178
QCNDCL=   1.388 QCNDD=   0.353 QCNDCN=   0.000 TGEXPA=1529.822 TGCMPA= 672.399 QSHTL=   1.939
QINB = 402.063 WRKBAS = 186.435 WALT = 183.283 QOUTB= 242.092 WRKLEX=  19.981 WRKLCM=   5.398 WLEXR=   3.767
WLCMR=   2.663 WLEXE=   9.274 WLCME=   1.312 WRKLR=   6.430 WRKLH=   6.940 WRKLC=   1.423 WRKLE=  10.587 WLALT=  22.227

* CYCLE NO    5 *
  TIME    ANGLE    X(1)  X(2) TRIN      TROUT       T1     T2        PE      PC      PRIN    PROUT    FRIN     FROUT
 0 0599   360.0  0.00  0.71  1484.87  716.85   1581.  698.  2562.99 2575.32 2563.88 2569.98-0.05633-0.23828
 0.0749   360.0  0.00  0.71  1494.37  721.81   1585.  697.  2568.83 2568.83 2568.83 2568.83-0.05616-0.23831
 TG=         1584.   1615.              1666.   1494.              722.    705.             707.    697.
TGA=   1585.   1584.   1615.   1671.   1664.   1416.    794.    721.    704.    700.    707.    697.
 TM=   1643.   1672.   1672.   1672.   1672.   1416.    796.    646.    656.    656.    646.    594.
QIN= 398.079 QOUT= 256.862 WRKEXP= 395.727 WRKCMP=-209.382 WRKTOT= 160.966 EFFTOT=   0.404 REFF1=   1.003 REFF2=   1.000
QREGEN= -14.004 PWRHP=  19.544 FREQ=  66.780 WRKLT=  25.379 UTOTAL=      0.000
EN3PM=  6310.710 AVGWSP= 2269.482
QEXPN=  -4.668 QEXPP=   0.124 QHEATN=-386.791 QHEATP=   2.115 QCOOLN=  -5.736 QCOOLP= 197.080 QCOMPN=   0.000 QCOMPP=   3.533
QREGN=-1829.721 QREGP=1815.717 QCNDRI=  5.178 QCNDRO=  5.178
QCNDCL=   1.388 QCNDD=   0.353 QCNDCN=   0.000 TGEXPA=1533.308 TCCMPA= 669.501 QSHTL=   1.939
QINB = 389.221 WRKBAS = 186.345 WALT = 186.345 QOUTB= 194.877 WRKLEX=   0.000 WRKLCM=   0.008 WLEXR=   0.000
WLCMR=   0.003 WLEXE=   0.000 WLCME=   0.003 WRKLR=   6.430 WRKLH=   6.940 WRKLC=   1.423 WRKLE=  10.587 WLALT=   0.000

** AVERAGE VALUES OVER LAST 5 CYCLES **

QIN= 422.757 QOUT= 318.618 WRKEXP= 396.414 WRKCMP=-214.058 WRKTOT= 177.280 EFFTOT=   0.421 REFF1=   0.991 REFF2=   0.981
QREGEN=   2.109 PWRHP=  21.525 FREQ=  66.780 WRKLT=  10.152 UTOTAL=      0.000
EN3PM=  6310.710 AVGWSP= 2281.762
QEXPN=  -5.189 QEXPP=   0.065 QHEATN=-419.000 QHEATP=   0.914 QCOOLN=  -1.960 QCOOLP= 263.946 QCOMPN=  -1.092 QCOMPP=   1.336
QREGN=-1820.829 QREGP=1822.939 QCNDRI=  2.071 QCNDRO=  2.071
QCNDCL=   0.555 QCNDD=   0.141 QCNDCN=   0.000 TGEXPA=1520.694 TGCMPA= 690.978 QSHTL=   0.776
QINB = 423.210 WRKBAS = 187.432 WALT = 186.801 QOUTB= 262.230 WRKLEX=   3.996 WRKLCM=   1.081 WLEXR=   0.753
WLCMR=   0.533 WLEXE=   1.855 WLCME=   0.263 WRKLR=   2.572 WRKLH=   2.776 WRKLC=   0.569 WRKLE=   4.235 WLALT=   4.445

** AVG. TEMPS.--LAST 5 CYCLES, AVG. H. T. COEFS. & HEAT FLUXES--LAST CYCLE **

 TGCYC=          1526.   1524.              1524.   1485               713.    702.             683.    673.
TGACYC=    1533.    1523.    1542.    1542.    1506.    1408.     790.     708.     691.     681.     678.     670.
 TMCYC=    1643.    1672.    1672.    1672.    1672.    1407.     790.     646.     656.     656.     646.     594.
 HACYC=    0.057    0.000    0.835    0.836    0.000    1.965    1.924    0.000    0.640    0.689    0.000    0.077
  HMX=    0 401    0.000    1.467    1.488    0.000    3.034    2.848    0.000    1.054    1.124    0.000    0.248
QOAAVG=     6.00     0.00    72.41    74.46     0.00     4.55     4.46     0.00    21.83    19.25     0.00     6.02
 QOAMX=    24.19     0.00   140.12   127.07     0.00    10.33     8.71     0.00    46.45    59.67     0.00    29.20
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```
 * CYCLE NO.  6 *
  TIME    ANGLE   X(1)   X(2) TRIN      TROUT       T1     T2       PE       PC      PRIN    PROUT     FRIN     FROUT
 0 0749    360 0  0.00   0.71  1494.37  721 81     1585.   697.   2568.83 2568.83 2568 83 2568.83-0.05616-0.23831
 0 0398    360.0  0.00   0.71  1490.89  721.98     1585.   697.   2568.12 2568.12 2568.12 2568.12-0.05622-0.23828
 TG=        1585.   1615.           1666.   1491.                  722.    705.                   707.    697.
 TCA=   1585    1585.    1615.    1671.    1664.    1413     795.     721.     704.     700.     707.     697.
 TM=    1643.   1672.    1672     1672.    1672.    1413.    796.     646.     656.     656.     646.     594.
QIN= 399 382 QOUT= 260.451 WRKEXP= 395.311 WRKCMP=-209.615 WRKTOT= 160.317 EFFTOT=   0.401 REFF1=   1.001 REFF2=   1.000
QREGEN=  -4.931 PWRHP=  19.465 FREQ=  66.780 WRKLT=  25.379 UTOTAL=      0.000
EN3PM=   6310.710 AVGWSP= 2268.878
QEXPN=  -4.664 QEXPP=   0.137 QHEATN=-388.539 QHEATP=   2.543 QCOOLN=  -5.600 QCOOLP= 200.579 QCOMPN=    0.000 QCOMPP=   3.509
QREGN=-1817 369 QREGP=1812.438 QCNDRI=  5.178 QCNDRO=  5.178
QCNDCL=   1.388 QCNDD=   0.353 QCNDCN=   0.000 TGEXPA=1534.179 TGCMPA= 668.912 QSHTL=   1.939
QINB = 390.523 WRKBAS = 185.696 WALT = 185.696 QOUTB= 198.488 WRKLEX=   0.000 WRKLCM=  -0.000 WLEXR=   0.000
WLCMR=  -0 000 WLEXE=   0 000 WLCME=  -0.000 WRKLR=   6.430 WRKLH=   6.940 WRKLC=   1.423 WRKLE=  10.587 WLALT=   0.000

 * CYCLE NO   7 *
  TIME    ANGLE   X(1)   X(2) TRIN      TROUT       T1     T2       PE       PC      PRIN    PROUT     FRIN     FROUT
 0 0898    360.0  0.00   0.71  1490.89  721.98     1585.   697.   2568.12 2568.12 2568.12 2568.12-0.05622-0.23828
 0 1048    360.0  0.00   0.71  1488.24  722.23     1585.   697.   2564 18 2576.51 2565.07 2571.16-0.05626-0.23824
 TG=        1584.   1614.           1665.   1488                   722.    705.                   707.    697.
 TGA=   1585    1584.    1615.    1671.    1663.    1411.    795.     721      704.     701.     707.     697.
 TM=    1643.   1672.    1672.    1672     1672.    1411.    796.     646.     656.     656.     646.     594.
QIN= 382.149 QOUT= 267.250 WRKEXP= 374.903 WRKCMP=-215.062 WRKTOT= 159.840 EFFTOT=   0.418 REFF1=   1.001 REFF2=   0.999
QREGEN=  -4 851 PWRHP=  19 408 FREQ=  66.780 WRKLT=  25.350 UTOTAL=      0.000
EN3PM=   6310.710 AVGWSP= 2268.445
QEXPN=  -4 680 QEXPP=   0.136 QHEATN=-391.210 QHEATP=   2.510 QCOOLN=  -5.469 QCOOLP= 201.870 QCOMPN=    0.000 QCOMPP=   3.506
QREGN=-1812.870 QREGP=1808.019 QCNDRI=  5.178 QCNDRO=  5.178
QCNDCL=   1.388 QCNDD=   0.361 QCNDCN=   0 000 TGEXPA=1533.792 TGCMPA= 668.810 QSHTL=   1.939
QINB = 393.243 WRKBAS = 185.190 WALT = 182.044 QOUTB= 199.907 WRKLEX=  19.961 WRKLCM=   5.389 WLEXR=   3.768
WLCMR=   2 649 WLEXE=   9.261 WLCME=   1.317 WRKLR=   6.417 WRKLH=   6.931 WRKLC=   1.424 WRKLE=  10.578 WLALT=  22.204

 * CYCLE NO   8 *
  TIME    ANGLE   X(1)   X(2) TRIN      TROUT       T1     T2       PE       PC      PRIN    PROUT     FRIN     FROUT
 0 1048    360.0  0.00   0.71  1488.24  722.23     1585.   697.   2564.18 2576.51 2565.07 2571.16-0.05626-0.23824
 0.1198    360.0  0.00   0.71  1491.98  708.28     1583.   689.   2543.65 2543.65 2543.65 2543.65-0.05597-0.23882
 TG=        1582.   1613.           1665.   1492.                  708.    692.                   697.    689.
 TGA=   1583.   1582.    1613.    1670.    1663.    1413.    783.     707.     691.     689.     697.     689.
 TM=    1643.   1672.    1672.    1672.    1672.    1413.    785.     646.     642.     642.     646.     592.
QIN= 400.120 QOUT= 288.393 WRKEXP= 397.424 WRKCMP=-207.759 WRKTOT= 164.316 EFFTOT=   0.411 REFF1=   0.996 REFF2=   0.999
QREGEN=  45.184 PWRHP=  19.951 FREQ=  66.780 WRKLT=  25.350 UTOTAL=      0.000
EN3PM=   6310.710 AVGWSP= 2253 392
QEXPN=  -4.692 QEXPP=   0.124 QHEATN=-388.856 QHEATP=   2.170 QCOOLN=  -3.186 QCOOLP= 227.849 QCOMPN=    0.000 QCOMPP=   3.371
QREGN=-1809.218 QREGP=1854 402 QCNDRI=  5.178 QCNDRO=  5.178
QCNDCL=   1.388 QCNDD=   0.361 QCNDCN=   0.000 TGEXPA=1532.464 TGCMPA= 664.988 QSHTL=   1.939
QINB = 391 254 WRKBAS = 189.665 WALT = 189.665 QOUTB= 228.034 WRKLEX=   0.000 WRKLCM=   0.008 WLEXR=   0.000
WLCMR=   0.003 WLEXE=   0.000 WLCME=   0.003 WRKLR=   6.417 WRKLH=   6.931 WRKLC=   1.424 WRKLE=  10.578 WLALT=   0.000

 * CYCLE NO.  9 *
  TIME    ANGLE   X(1)   X(2) TRIN      TROUT       T1     T2       PE       PC      PRIN    PROUT     FRIN     FROUT
 0 1198    360.0  0.00   0.71  1491.98  708.28     1583.   689.   2543.65 2543.65 2543.65 2543.65-0.05597-0.23882
 0 1348    360 0  0.00   0.71  1490.10  709.14     1584.   686.   2543.24 2543.24 2543.24 2543.24-0.05608-0.23857
 TG=        1583.   1614.           1665.   1490.                  709.    692.                   696.    686.
 TGA=   1584    1583.    1614.    1671.    1663.    1411.    787.     708.     691.     688.     696.     686.
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 0 1947    360.0  0.00  0.71  1486.88  708.68   1587.    683.  2446.02 2458.08 2446.86 2452.88-0.05327-0.23035
 TG=         1586.   1617.              1668.   1487                   709.    691.              693.    683.
TGA=   1587.    1586.    1617.    1674.    1666.    1408.     784.     708.     690.     687.     693.     683.
 TM=   1643.    1672.    1672.    1672.    1672.    1408.     785.     646.     642.     642.     646.     592.
QIN= 384.193 QOUT= 258.590 WRKEXP= 363.144 WRKCMP=-202.837 WRKTOT= 160.307 EFFTOT=   0.417 REFF1=   0.997 REFF2=   0.996
QREGEN=   1.387 PWRHP=  19.464 FREQ=  66.780 WRKLT=  24.834 UTOTAL=      0.000
EN3PM=  6310.710 AVGWSP= 2170.841
QEXPN=  -4.357 QEXPP=    0 132 QHEATN=-373.808 QHEATP=   2.712 QCOOLN=  -4.873 QCOOLP= 200.910 QCOMPN=   0.000 QCOMPP=   2.855
QREGN=-1774.058 QREGP=1775.445 QCNDRI=  5.178 QCNDRO=  5.178
QCNDCL=   1.388 QCNDD=   0.368 QCNDCN=    0.000 TGEXPA=1538.428 TGCMPA= 655.407 QSHTL=   1.939
QINB = 375.320 WRKBAS = 185.141 WALT = 182.140 QOUTB= 198.893 WRKLEX=  19.584 WRKLCM=   5.250 WLEXR=   3.806
WLCMR=   2.604 WLEXE=   8.988 WLCME=   1.272 WRKLR=   6.410 WRKLH=   6.791 WRKLC=   1.375 WRKLE=  10.259 WLALT=  21.833

* CYCLE NO. 14 *
  TIME    ANGLE    X(1)   X(2) TRIN      TROUT       T1      T2        PE      PC      PRIN   PROUT    FRIN      FROUT
 0.1947    360.0  0.00  0.71  1486.88  708.68   1587.  683.  2446.02 2458.08 2446.86 2452.88-0.05327-0.23035
 0 2096    360.0  0.00  0.71  1486.99  708.67   1587.  683.  2449.86 2449.86 2449.86 2449.86-0.05327-0.23035
 TG=         1586.   1617.              1668.   1487.                  709.    691.              693.    683.
TGA=   1587.    1587.    1617.    1674.    1666.    1408.     784.     707.     690.     687.     693.     683.
 TM=   1643.    1672.    1672.    1672.    1672.    1408.     786.     646.     642.     642.     646.     592.
QIN= 384.042 QOUT= 259.159 WRKEXP= 382.789 WRKCMP=-197.619 WRKTOT= 160.335 EFFTOT=   0.417 REFF1=   0.997 REFF2=   0.996
QREGEN=   0.993 PWRHP=  19.468 FREQ=  66.780 WRKLT=  24.834 UTOTAL=      0.000
EN3PM=  6310.710 AVGWSP= 2171.016
QEXPN=  -4.355 QEXPP=    0.133 QHEATN=-373.677 QHEATP=   2.730 QCOOLN=  -4.826 QCOOLP= 201.423 QCOMPN=   0.000 QCOMPP=   2.861
QREGN=-1774.433 QREGP=1775.425 QCNDRI=  5.178 QCNDRO=  5.178
QCNDCL=   1.388 QCNDD=   0.368 QCNDCN=    0.000 TGEXPA=1538.491 TGCMPA= 655.475 QSHTL=   1.939
QINB = 375.169 WRKBAS = 185.170 WALT = 185.170 QOUTB= 199.458 WRKLEX=   0.000 WRKLCM=   0.008 WLEXR=   0.000
WLCMR=   0.003 WLEXE=   0.000 WLCME=   0.003 WRKLR=   6.410 WRKLH=   6.791 WRKLC=   1.375 WRKLE=  10.259 WLALT=   0.000

* CYCLE NO. 15 *
  TIME    ANGLE    X(1)   X(2) TRIN      TROUT       T1      T2        PE      PC      PRIN   PROUT    FRIN      FROUT
 0 2096    360.0  0.00  0.71  1486.99  708.67   1587.  683.  2449.86 2449.86 2449.86 2449.86-0.05327-0.23035
 0.2246    360.0  0.00  0.71  1487.08  708.70   1587.  683.  2450.00 2450.00 2450.00 2450.00-0.05327-0.23034
 TG=         1586.   1617.              1668.   1487.                  709.    691.              693.    683.
TGA=   1587.    1587.    1617.    1674.    1666.    1408.     784.     708.     690.     687.     693.     683.
 TM=   1643.    1672.    1672.    1672.    1672.    1408.     786.     646.     642.     642.     646.     592.
QIN= 383.931 QOUT= 259.342 WRKEXP= 382.818 WRKCMP=-197.625 WRKTOT= 160.359 EFFTOT=   0.418 REFF1=   0.997 REFF2=   0.996
QREGEN=   0.728 PWRHP=  19.470 FREQ=  66.780 WRKLT=  24.834 UTOTAL=      0.000
EN3PM=  6310.710 AVGWSP= 2171 144
QEXPN=  -4 354 QEXPP=    0.133 QHEATN=-373.575 QHEATP=   2.739 QCOOLN=  -4.811 QCOOLP= 201.584 QCOMPN=   0.000 QCOMPP=   2.862
QREGN=-1774.656 QREGP=1775.384 QCNDRI=  5.178 QCNDRO=  5.178
QCNDCL=   1.388 QCNDD=   0.368 QCNDCN=    0.000 TGEXPA=1538.527 TGCMPA= 655.506 QSHTL=   1.939
QINB = 375.058 WRKBAS = 185.193 WALT = 185.193 QOUTB= 199.635 WRKLEX=   0.000 WRKLCM=  -0.000 WLEXR=   0.000
WLCMR=  -0.000 WLEXE=   0.000 WLCME=  -0.000 WRKLR=   6.410 WRKLH=   6.791 WRKLC=   1.375 WRKLE=  10.259 WLALT=   0.000


** AVERAGE VALUES OVER LAST 5 CYCLES **

QIN= 384.380 QOUT= 258.507 WRKEXP= 378.788 WRKCMP=-198.626 WRKTOT= 160.277 EFFTOT=   0.417 REFF1=   0.997 REFF2=   0.996
QREGEN=   0.561 PWRHP=  19.461 FREQ=  66.780 WRKLT=  24.851 UTOTAL=      0.000
EN3PM=  6310.710 AVGWSP= 2170.770
QEXPN=  -4.359 QEXPP=    0.131 QHEATN=-373.933 QHEATP=   2.654 QCOOLN=  -4.875 QCOOLP= 200.844 QCOMPN=   0.000 QCOMPP=   2.852
QREGN=-1774 774 QREGP=1775.335 QCNDRI=  5.178 QCNDRO=  5.178
QCNDCL=   1.388 QCNDD=   0.368 QCNDCN=    0.000 TGEXPA=1538.285 TGCMPA= 655.329 QSHTL=   1.939
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QINB = 375.507 WRKBAS = 185.129 WALT = 184.529 QOUTB= 198.821 WRKLEX=   3.917 WRKLCM=   1.053 WLEXR=   0.761
WLCMR=   0.522 WLEXE=   1.798 WLCME=   0.256 WRKLR=   6.410 WRKLH=   6.796 WRKLC=   1.376 WRKLE=  10.270 WLALT=   4.367


** AVG  TEMPS.--LAST 5 CYCLES, AVG. H. T. COEFS. & HEAT FLUXES--LAST CYCLE **

 TGCYC=       1530.   1528.           1524.   1482.             702.    690.              669.    659.
TGACYC=   1539    1527.   1545.   1542.   1505.   1400.    780.    696.    679.    668.    665.    656.
 TMCYC=   1643.   1672.   1672.   1672.   1672.   1400.    780.    646.    642.    642.    646.    592.
 HACYC=   0.057   0.000   0.808   0.810   0.000   1.922   1.879   0.000   0.622   0.671   0.000   0.075
  HMX=   0 444   0.000   1 412   1.435   0.000   2.949   2.779   0.000   1.027   1.099   0.000   0.245
QOAAVG=    5.66    0.00   69.19   72.96    0.00    4.45    4.38    0.00   22.62   19.19    0.00    5.01
 QOAMX=   22 99    0.00  132.72  128.79    0.00    8.45    8.52    0.00   46.24   59.02    0.00   25.80


* CYCLE NO. 16 *
  TIME    ANGLE   X(1)  X(2) TRIN     TROUT      T1     T2       PE      PC      PRIN   PROUT    FRIN     FROUT
 0 2246    360.0  0.00  0.71  1487.08  708.70    1587.  683.  2450.00 2450.00 2450.00 2450.00-0.05327-0.23034
 0 2396    360.0  0.00  0.71  1487.16  708.72    1587.  683.  2446.43 2458.49 2447.26 2453.28-0.05327-0.23034
 TG=      1586.   1617.          1668.   1487.              709.    691.              693.    683.
TGA=   1587.   1587.   1617.   1674.   1666.   1408.    784.    708.    690.    687.    693.    683.
 TM=   1643.   1672.   1672.   1672.   1672.   1408.    786.    646.    642.    642.    646.    592.
QIN= 383.845 QOUT= 259.495 WRKEXP= 363.255 WRKCMP=-202.888 WRKTOT= 160.368 EFFTOT=   0.418 REFF1=   0.997 REFF2=   0.996
QREGEN=   0.598 PWRHP=  19.472 FREQ=  66.780 WRKLT=  24.837 UTOTAL=      0.000
ENSPM=  6310.710 AVGWSP= 2171.243
QEXPN=  -4 354 QEXPP=    0.133 QHEATN=-373.496 QHEATP=    2.744 QCOOLN=  -4.799 QCOOLP= 201.722 QCOMPN=    0.000 QCOMPP=    2.863
QREGN=-1774.759 QREGP=1775 357 QCNDRI=  5.178 QCNDRO=  5.178
QCNDCL=   1.388 QCNDD=    0.368 QCNDCN=    0 000 TGEXPA=1538.553 TGCMPA= 655.527 QSHTL=    1.939
QINB = 374.972 WRKBAS = 185.205 WALT = 182.203 QOUTB= 199.786 WRKLEX=  19.587 WRKLCM=   5.251 WLEXR=   3.807
WLCMR=   2.604 WLEXE=   8.988 WLCME=   1.272 WRKLR=   6.412 WRKLH=   6.791 WRKLC=   1.375 WRKLE=  10.260 WLALT=  21.836

* CYCLE NO. 17 *
  TIME    ANGLE   X(1)  X(2) TRIN     TROUT      T1     T2       PE      PC      PRIN   PROUT    FRIN     FROUT
 0 2396    360.0  0.00  0.71  1487.16  708.72    1587.  683.  2446.43 2458.49 2447.26 2453.28-0.05327-0.23034
 0 2546    360.0  0.00  0.71  1487.22  708.81    1587.  683.  2450.29 2450.29 2450.29 2450.29-0.05327-0.23034
 TG=      1586.   1617.          1668.   1487.              709.    691.              693.    683.
TGA=   1587.   1587.   1617.   1674.   1666.   1409.    784.    708.    690.    687.    693.    683.
 TM=   1643.   1672.   1672.   1672.   1672.   1408.    786.    646.    642.    642.    646.    592.
QIN= 383 768 QOUT= 259.249 WRKEXP= 382.843 WRKCMP=-197.659 WRKTOT= 160.347 EFFTOT=   0.418 REFF1=   0.997 REFF2=   0.996
QREGEN=   0.554 PWRHP=  19.469 FREQ=  66.780 WRKLT=  24.837 UTOTAL=      0.000
ENSPM=  6310.710 AVGWSP= 2171.364
QEXPN=  -4.353 QEXPP=    0.134 QHEATN=-373.424 QHEATP=    2.749 QCOOLN=  -4.822 QCOOLP= 201.491 QCOMPN=    0.000 QCOMPP=    2.863
QREGN=-1774.784 QREGP=1775.338 QCNDRI=  5.178 QCNDRO=  5.178
QCNDCL=   1.388 QCNDD=    0 368 QCNDCN=    0.000 TGEXPA=1538.579 TGCMPA= 655.563 QSHTL=    1.939
QINB = 374 895 WRKBAS = 185.184 WALT = 185.184 QOUTB= 199.532 WRKLEX=   0.000 WRKLCM=   0.008 WLEXR=   0.000
WLCMR=   0.003 WLEXE=   0.000 WLCME=   0.003 WRKLR=   6.412 WRKLH=   6.791 WRKLC=   1.375 WRKLE=  10.260 WLALT=   0.000

* CYCLE NO. 18 *
  TIME    ANGLE   X(1)  X(2) TRIN     TROUT      T1     T2       PE      PC      PRIN   PROUT    FRIN     FROUT
 0 2546    360.0  0 00  0.71  1487.22  708.81    1587.  683.  2450.29 2450.29 2450.29 2450.29-0.05327-0.23034
 0.2695    360.0  0.00  0 71  1487.27  708.82    1587.  683.  2450.38 2450.38 2450.38 2450.38-0.05327-0.23034
 TG=      1586.   1617.          1668.   1487.              709.    691.              693.    683.
TGA=   1587.   1587.   1617.   1674.   1666.   1409.    784.    708.    690.    687.    693.    683.
 TM=   1643.   1672.   1672.   1672.   1672.   1409.    786.    646.    642.    642.    646.    592.
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QIN= 383.717 QOUT= 259.456 WRKEXP= 382.868 WRKCMP=-197.667 WRKTOT= 160.363 EFFTOT=   0.418 REFF1=   0.997 REFF2=   0.996
QRECEN=   0.554 PWRHP=  19.471 FREQ=  66.780 WRKLT=  24.837 UTOTAL=     0.000
EN3PM=  6310.710 AVGWSP= 2171.462
QEXPN=  -4.353 QEXPP=   0.134 QHEATN=-373.378 QHEATP=   2.753 QCOOLN=  -4.808 QCOOLP= 201.681 QCOMPN=   0.000 QCOMPP=   2.866
QREGN=-1774 769 QREGP=1775.323 QCNDRI=  5.178 QCNDRO=  5 178
QCNDCL=   1.388 QCNDD=   0.368 QCNDCN=   0 000 TGEXPA=1538.595 TGCMPA= 655.604 QSHTL=   1.939
QINB = 374.844 WRKBAS = 185.200 WALT = 185.200 QOUTB= 199.739 WRKLEX=   0.000 WRKLCM=  -0.000 WLEXR=   0.000
WLCMR=  -0 000 WLEXE=   0.000 WLCME=  -0.000 WRKLR=   6.412 WRKLH=   6.791 WRKLC=   1.375 WRKLE=  10.260 WLALT=   0.000

* CYCLE NO  19 *
  TIME    ANGLE   X(1)  X(2) TRIN     TROUT      T1     T2       PE      PC      PRIN   PROUT    FRIN     FROUT
 0 2695   360 0   0.00  0.71  1487.27  708.82    1587.  683.  2450.38 2450.38 2450.38 2450.38-0.05327-0.23034
 0 2845   360.0   0.00  0.71  1487.31  708.84    1587.  683.  2446.78 2458.84 2447.61 2453.64-0.05327-0.23034
 TG=        1586.    1617.           1668.   1487.                709.    691.              693.    683.
TGA=   1587.   1587.   1617.   1674.   1666.   1409.    785.    708.    690.    687.    693.    683.
 TM=   1643    1672.   1672.   1672.   1672.   1409.    786.    646.    642.    642.    646.    592.
QIN= 383 677 QOUT= 259.590 WRKEXP= 363.296 WRKCMP=-202.929 WRKTOT= 160.367 EFFTOT=   0.418 REFF1=   0.997 REFF2=   0.996
QREGEN=   0.443 PWRHP=  19.472 FREQ=  66.780 WRKLT=  24.839 UTOTAL=     0.000
EN3PM=  6310.710 AVGWSP= 2171.535
QEXPN=  -4.352 QEXPP=   0.134 QHEATN=-373.341 QHEATP=   2.756 QCOOLN=  -4.797 QCOOLP= 201.802 QCOMPN=   0.000 QCOMPP=   2.867
QREGN=-1774.848 QREGP=1775 291 QCNDRI=  5.178 QCNDRO=  5.178
QCNDCL=   1.388 QCNDD=   0.368 QCNDCN=   0.000 TGEXPA=1538.606 TGCMPA= 655.631 QSHTL=   1.939
QINB = 374.804 WRKBAS = 185.206 WALT = 182.205 QOUTB= 199.872 WRKLEX=  19.588 WRKLCM=   5.251 WLEXR=   3.808
WLCMR=   2.605 WLEXE=   8.989 WLCME=   1.272 WRKLR=   6.413 WRKLH=   6.791 WRKLC=   1.375 WRKLE=  10.261 WLALT=  21.837

* CYCLE NO. 20 *
  TIME    ANGLE   X(1)  X(2) TRIN     TROUT      T1     T2       PE      PC      PRIN   PROUT    FRIN     FROUT
 0 2845   360.0   0.00  0.71  1487.31  708.84    1587.  683.  2446.78 2458.84 2447.61 2453.64-0.05327-0.23034
 0 2995   360.0   0.00  0.71  1487.34  708.90    1587.  683.  2446.90 2458.96 2447.73 2453.75-0.05327-0.23033
 TG=        1586.    1617.           1668.   1487.                709.    691.              694.    683.
TGA=   1587.   1587.   1617.   1674.   1666.   1409.    785.    708.    690.    687.    693.    683.
 TM=   1643.   1672    1672.   1672.   1672.   1409.    786.    646.    642.    642.    646.    592.
QIN= 383 640 QOUT= 259.469 WRKEXP= 363.297 WRKCMP=-202.948 WRKTOT= 160.350 EFFTOT=   0.418 REFF1=   0.997 REFF2=   0.996
QREGEN=   0.404 PWRHP=  19.469 FREQ=  66.780 WRKLT=  24.848 UTOTAL=     0.000
EN3PM=  6310.710 AVGWSP= 2171.620
QEXPN=  -4.352 QEXPP=   0 134 QHEATN=-373.307 QHEATP=   2.758 QCOOLN=  -4.809 QCOOLP= 201.687 QCOMPN=   0.000 QCOMPP=   2.868
QREGN=-1774.855 QREGP=1775 260 QCNDRI=  5.178 QCNDRO=  5.178
QCNDCL=   1.388 QCNDD=   0.368 QCNDCN=   0.000 TGEXPA=1538.620 TGCMPA= 655.661 QSHTL=   1.939
QINB = 374 767 WRKBAS = 185.197 WALT = 182.188 QOUTB= 199.746 WRKLEX=  19.588 WRKLCM=   5.259 WLEXR=   3.808
WLCMR=   2 608 WLEXE=   8.989 WLCME=   1.275 WRKLR=   6.416 WRKLH=   6.791 WRKLC=   1.377 WRKLE=  10.264 WLALT=  21.838


** AVERAGE VALUES OVER LAST 5 CYCLES **

QIN= 383.729 QOUT= 259.452 WRKEXP= 371.112 WRKCMP=-200.818 WRKTOT= 160.359 EFFTOT=   0.418 REFF1=   0.997 REFF2=   0.996
QREGEN=   0.511 PWRHP=  19.470 FREQ=  66.780 WRKLT=  24.840 UTOTAL=     0.000
EN3PM=  6310 710 AVGWSP= 2171.445
QEXPN=  -4.353 QEXPP=   0.134 QHEATN=-373.389 QHEATP=   2.752 QCOOLN=  -4.807 QCOOLP= 201.677 QCOMPN=   0.000 QCOMPP=   2.865
QREGN=-1774 803 QREGP=1775.314 QCNDRI=  5.178 QCNDRO=  5.178
QCNDCL=   1.388 QCNDD=   0.368 QCNDCN=   0.000 TGEXPA=1538.591 TGCMPA= 655.597 QSHTL=   1.939
QINB = 374 856 WRKBAS = 185.199 WALT = 183.396 QOUTB= 199.735 WRKLEX=  11.753 WRKLCM=   3.154 WLEXR=   2.285
WLCMR=   1.564 WLEXE=   5.393 WLCME=   0.764 WRKLR=   6.413 WRKLH=   6.791 WRKLC=   1.375 WRKLE=  10.261 WLALT=  13.102
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** AVG. TEMPS.--LAST 5 CYCLES, AVG. H. T. COEFS. & HEAT FLUXES--LAST CYCLE **

 TCCYC=        1530.   1528.              1524.   1482.              703.    691.               669.    659.
TGACYC=   1539.   1527.   1545.   1543.   1505.   1400.    780.    697.    679.    668.    665.    656.
 TMCYC=   1643.   1672.   1672.   1672.   1672.   1400.    780.    646.    642.    642.    646.    592.
 HACYC=   0.057   0.000   0.808   0.810   0.000   1.922   1.879   0.000   0.622   0.672   0.000   0.075
   HMX=  0.444   0.000   1.412   1.435   0.000   2.949   2.779   0.000   1.027   1.099   0.000   0.245
QOAAVG=    5.65    0.00   69.15   72.90    0.00    4.45    4.38    0.00   22.64   19.20    0.00    5.02
 QOAMX=   22.92    0.00  132.68  128.64    0.00    8.45    8.52    0.00   46.23   59.02    0.00   25.83


* CYCLE NO  21 *
  TIME    ANGLE    X(1)   X(2) TRIN      TROUT      T1     T2       PE      PC      PRIN   PROUT    FRIN      FROUT
 0 2995    360.0   0.00   0.71  1487.34  708.90    1587.   683.   2446.90 2458.96 2447.73 2453.75-0.05327-0.23033
 0 3001     14.4   0.03   0.52  1485.75  700.03    1614.   695.   2587.92 2607.44 2593.97 2601.99-0.11060-0.26132
 0.3007     28.8   0.12   0.35  1483.80  694.10    1645.   703.   2691.60 2720.80 2706.57 2715.93-0.16240-0.26890
 0 3013     43.2   0.25   0.21  1481.42  689.33    1667.   707.   2748.13 2785.85 2772.35 2782.21-0.19812-0.24991
 0.3019     57.6   0.42   0.10  1478.76  684.29    1673.   708.   2756.66 2798.16 2786.50 2795.99-0.21164-0.20731
 0 3025     72.0   0.62   0.03  1476.06  678.27    1663.   705.   2722.45 2761.48 2752.22 2760.56-0.20240-0.14794
 0.3031     86.4   0.82   0.00  1473.57  671.10    1643.   699.   2653.89 2685.04 2678.34 2684.87-0.17352-0.07952
 0 3037    100.8   1.01   0.01  1471.45  662.95    1618.   691.   2559.59 2580.05 2575.85 2580.05-0.13060-0.00890
 0.3043    115.2   1 19   0.06  1469.78  692.98    1592.   683.   2446.70 2456.33 2455.00 2456.65-0.08194 0.06085
 0.3049    129.6   1.34   0.15  1468.14  695.38    1566.   672.   2324.08 2324.60 2326.67 2325.61-0.03289 0.11694
 0 3055    144.0   1.45   0.27  1410.40  696.81    1541.   660.   2196.98 2191.65 2197.13 2193.47 0.01133 0.16000
 0.3061    158.4   1.53   0.43  1391.33  698.39    1517.   647.   2072.12 2062.96 2071.59 2065.55 0.05149 0.19115
 0.3067    172 8   1.57   0.61  1381.49  700.19    1495.   635.   1959.38 1945.20 1956.55 1948.40 0.08421 0.21058
 0.3073    187.2   1.57   0.81  1384.14  702.11    1474.   624.   1861.41 1842.01 1855.23 1845.49 0.10744 0.21681
 0 3079    201.6   1 53   1.01  1399.00  704.04    1457.   616.   1780.48 1756.53 1770.65 1759.94 0.12198 0.21073
 0 3085    216.0   1.45   1.20  1422.41  705.88    1444.   610.   1718.92 1691.59 1705.65 1694.58 0.12957 0.19441
13 0 3091    230.4   1.34   1.36  1449.66  707.58    1435.   607.   1679.10 1649.65 1662.86 1652.00 0.13231 0.17031
 0 3097    244.8   1.19   1.49  1476.87  709.08    1431.   606.   1663.25 1632.88 1644.67 1634.49 0.13185 0.14047
 0.3103    259.2   1.01   1.56  1502.24  710.38    1434.   609.   1673.33 1643.26 1653.24 1644.16 0.12896 0.10597
 0.3109    273.6   0.82   1.57  1525.99  711.47    1443.   613.   1711.01 1682.57 1690.50 1682.90 0.12331 0.06687
 0.3115    288.0   0.62   1.53  1549.57  712.50    1458.   621.   1777.68 1752.57 1758.30 1752.55 0.11346 0.02235
 0.3121    302.4   0.42   1.43  1574.24  730.44    1478.   631.   1873.13 1853.32 1856.56 1852.83 0.09899-0.02473
 0 3127    316.8   0.25   1.28  1600.17  735.52    1503.   643.   1992.59 1980.71 1980.69 1979.20 0.07674-0.07476
 0.3133    331.2   0.12   1.11  1627.72  731.75    1530.   656.   2132.71 2130.48 2126.56 2127.59 0.04431-0.12968
 0 3139    345.6   0.03   0.91  1656.73  720.86    1559.   670.   2287.77 2294.28 2286.44 2290.04 0.00136-0.18351
 0.3145    360.0   0.00   0.71  1487.36  708.91    1587.   683.   2446.97 2459.03 2447.80 2453.82-0.05327-0.23033
 TG=        1586.   1617.                1668.   1487.                709.    691.               694.    683.
TGA=   1587.   1587.   1617.   1674.   1666.   1409.    785.    708.    690.    687.    693.    683.
 TM=   1643.   1672.   1672.   1672.   1672.   1409.    786.    646.    642.    642.    646.    592.
QIN= 383.617 QOUT= 259.622 WRKEXP= 363.312 WRKCMP=-202.959 WRKTOT= 160.353 EFFTOT=   0.418 REFF1=   0.997 REFF2=   0.996
QREGEN=   0.398 PWRHP=  19.470 FREQ=  66.780 WRKLT=  24.848 UTOTAL=       0.000
EN3PM=  6310.710 AVGWSP= 2171.688
QEXPN=  -4.352 QEXPP=   0.134 QHEATN=-373.286 QHEATP=   2.760 QCOOLN=  -4.798 QCOOLP= 201.827 QCOMPN=   0.000 QCOMPP=   2.870
QREGN=-1774.834 QREGP=1775.232 QCNDRI=  5.178 QCNDRO=  5.178
QCNDCL=   1.388 QCNDD=   0.368 QCNDCN=   0.000 TGEXPA=1538.627 TGCMPA= 655.691 QSHTL=   1.939
QINB = 374.744 WRKBAS = 185.201 WALT = 182.191 QOUTB= 199.899 WRKLEX=  19.589 WRKLCM=   5.259 WLEXR=   3.808
WLCMR=   2.608 WLEXE=   8.989 WLCME=   1.275 WRKLR=   6.416 WRKLH=   6.791 WRKLC=   1.377 WRKLE=  10.264 WLALT=  21.838

* CYCLE NO. 22 *
  TIME    ANGLE    X(1)   X(2) TRIN      TROUT      T1     T2       PE      PC      PRIN   PROUT    FRIN      FROUT
 0.3145    360.0   0.00   0.71  1487.36  708.91    1587.   683.   2446.97 2459.03 2447.80 2453.82-0.05327-0.23033
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 0 3151     14.4  0.03  0.52  1485.75  700.04   1614.  695.  2587.96 2607.48 2594.00 2602 02-0.11060-0.26132
 0 3157     28.8  0.12  0 35  1483 81  694.11   1645.  703.  2691.64 2720.84 2706.60 2715.97-0.16240-0.26890
 0 3163     43.2  0.25  0.21  1481 42  689.34   1667.  707.  2748.17 2785.89 2772.38 2782.25-0.19812-0.24990
 0.3169     57.6  0.42  0.10  1478.76  684.30   1673.  708.  2756.69 2798.20 2786.53 2796 02-0.21164-0.20730
 0.3175     72.0  0.62  0.03  1476.07  678.28   1663.  705.  2722.48 2761.51 2752.25 2760.59-0.20240-0.14794
 0 3181     86.4  0.82  0.00  1473.58  671.11   1643.  699.  2653.91 2685.07 2678.37 2684.90-0.17352-0.07952
 0.3187    100.8  1.01  0.01  1471.46  662.95   1618.  691.  2559.61 2580.08 2575.87 2580.07-0.13060-0.00890
 0.3193    115.2  1.19  0.06  1469 79  692.99   1592.  683.  2446.72 2456.35 2455.02 2456.67-0.08194 0.06085
 0 3199    129.6  1.34  0.15  1468.14  695.39   1566.  672.  2324.10 2324.62 2326.69 2325.63-0.03289 0.11694
 0 3205    144.0  1.45  0.27  1410.40  696.82   1541.  660.  2197.00 2191.67 2197.15 2193.49 0.01133 0.16000
 0 3211    158.4  1.53  0.43  1391.34  698.40   1517.  647.  2072.14 2062.98 2071.60 2065 57 0.05149 0.19115
 0 3217    172.8  1.57  0.61  1381.49  700.20   1495.  635.  1959.40 1945.22 1956.57 1948.42 0.08421 0 21058
 0.3223    187.2  1.57  0.81  1384.14  702.12   1474.  624.  1861.43 1842.03 1855.25 1845.51 0.10744 0.21681
 0 3229    201.6  1.53  1.01  1399.00  704.04   1457.  616.  1780.49 1756.55 1770.67 1759.95 0.12198 0.21073
 0 3235    216.0  1.45  1 20  1422.41  705.89   1444.  610.  1718.94 1691.61 1705.67 1694.60 0.12957 0.19441
 0.3240    230.4  1.34  1.36  1449.66  707.58   1435.  607.  1679.12 1649.67 1662.88 1652.02 0.13231 0.17031
 0 3246    244 8  1.19  1.49  1476.87  709.09   1431.  606.  1663.26 1632.90 1644.69 1634.51 0.13186 0.14047
 0 3252    259.2  1.01  1.56  1502.24  710.38   1434.  609.  1673.35 1643.27 1653.25 1644.17 0.12896 0.10597
 0 3258    273.6  0.82  1.57  1525.99  711.48   1443.  613.  1711.03 1682.58 1690.52 1682.91 0.12331 0.06687
 0.3264    288.0  0.62  1.53  1549.57  712.51   1458.  621.  1777.69 1752.58 1758.32 1752.57 0.11346 0.02235
 0.3270    302.4  0.42  1.43  1574 24  730.45   1478.  631.  1873.15 1853.34 1856.58 1852.85 0.09899-0.02473
 0.3276    316.8  0.25  1.28  1600.17  735.53   1503.  643.  1992.61 1980.73 1980.71 1979.22 0.07674-0.07476
 0 3282    331.2  0.12  1.11  1627.72  731.76   1530.  656.  2132.73 2130.50 2126.58 2127.61 0.04431-0.12968
 0.3288    345.6  0.03  0.91  1656.73  720.86   1559.  670.  2287.79 2294.30 2286.46 2290.06 0.00136-0.18351
 0.3294    360.0  0.00  0.71  1487.36  708.92   1587.  683.  2446.99 2459.05 2447.82 2453.85-0.05327-0.23033
  TG=        1586.    1617.             1668.    1487.             709.    691.             694.    683.
 TGA=   1587.    1587.    1617.    1674.    1666.    1409.    785.    708.    690.    687.    693.    683.
  TM=   1643.    1672.    1672.    1672.    1672.    1409.    786.    646.    642.    642.    646.    592.
QIN= 383.616 QOUT= 259.672 WRKEXP= 363.317 WRKCMP=-202.964 WRKTOT= 160.353 EFFTOT=   0.418 REFF1=   0.997 REFF2=   0.996
QREGEN=   0.517 PWRHP=  19.470 FREQ=  66.780 WRKLT=  24 848 UTOTAL=     0.000
EN3PM=  6310.710 AVGWSP= 2171 710
QEXPN=  -4.352 QEXPP=   0.134 QHEATN=-373.285 QHEATP=   2.760 QCOOLN=  -4.793 QCOOLP= 201.875 QCOMPN=   0.000 QCOMPP=   2.870
QREGN=-1774.713 QREGP=1775.230 QCNDRI=  5.178 QCNDRO=  5.178
QCNDCL=   1.388 QCNDD=   0 368 QCNDCN=   0.000 TGEXPA=1538.626 TGCMPA= 655.708 QSHTL=   1.939
QINB = 374.743 WRKBAS = 185.202 WALT = 182.192 QOUTB= 199.952 WRKLEX=  19.589 WRKLCM=   5.260 WLEXR=   3.808
WLCMR=   2.608 WLEXE=   8.989 WLCME=   1.275 WRKLR=   6.416 WRKLH=   6.791 WRKLC=   1.377 WRKLE=  10.264 WLALT=  21.838

 * CYCLE NO. 23 *
  TIME    ANGLE   X(1)  X(2) TRIN      TROUT      T1     T2        PE      PC      PRIN   PROUT     FRIN      FROUT
 0.3294    360.0  0.00  0.71  1487.36  708.92   1587.  683.  2446.99 2459.05 2447.82 2453.85-0.05327-0.23033
 0 3300     14.4  0.03  0.52  1485.75  700.04   1614.  695.  2587.98 2607.50 2594.02 2602.04-0.11060-0.26132
 0 3306     28.8  0.12  0.35  1483.81  694.11   1645.  703.  2691.66 2720 86 2706.62 2715.99-0.16240-0.26890
 0 3312     43.2  0.25  0.21  1481.42  689.35   1667.  708.  2748.19 2785.91 2772.41 2782.27-0.19812-0.24990
 0 3318     57.6  0.42  0.10  1478.76  684.30   1673.  708.  2756.71 2798.22 2786.55 2796.04-0.21164-0.20730
 0.3324     72.0  0.62  0.03  1476.07  678.28   1663.  705.  2722.50 2761.53 2752.27 2760.61-0.20240-0.14794
 0 3330     86.4  0.82  0.00  1473.58  671.12   1643.  699.  2653.93 2685.09 2678.39 2684.91-0.17352-0.07952
 0 3336    100.8  1.01  0.01  1471.46  662.96   1618.  691.  2559.63 2580.09 2575.89 2580.09-0.13060-0.00890
 0.3342    115 2  1.19  0.06  1469.79  692.99   1592.  683.  2446.74 2456.37 2455.04 2456.69-0.08194 0.06085
 0.3348    129.6  1.34  0.15  1468.15  695.40   1566.  672.  2324.12 2324.64 2326.70 2325.65-0.03289 0.11694
 0 3354    144.0  1.45  0 27  1410.40  696.83   1541   660.  2197.01 2191.69 2197.16 2193.51 0.01133 0.16000
 0.3360    158.4  1.53  0.43  1391.34  698.41   1517.  647.  2072.15 2062.99 2071.62 2065.58 0.05149 0.19115
 0 3366    172.8  1.57  0.61  1381.49  700.21   1495.  635.  1959.41 1945.23 1956.58 1948.43 0.08421 0.21058
 0 3372    187.2  1.57  0.81  1384.15  702.12   1474.  624.  1861.44 1842.04 1855.26 1845.52 0.10744 0.21681
 0 3378    201.6  1.53  1.01  1399.00  704.05   1457.  616.  1780.50 1756.56 1770.68 1759.96 0.12198 0.21073
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 0 3384    216.0  1.45  1.20  1422.42  705.90   1444.  610.  1718.95 1691.62 1705.68 1694.61 0.12957 0.19441
 0 3390    230 4  1.34  1.36  1449.66  707.59   1435.  607.  1679.13 1649.68 1662.89 1652.03 0.13231 0.17031
 0 3396    244.8  1.19  1.49  1476.87  709.10   1431.  606.  1663.27 1632.91 1644.70 1634.52 0.13186 0.14047
 0 3402    259.2  1.01  1.56  1502.24  710.39   1434.  609.  1673.36 1643.28 1653.26 1644.18 0.12896 0.10597
 0.3408    273.6  0.82  1.57  1525.99  711.48   1443.  613.  1711.04 1682.59 1690.53 1682.92 0.12331 0.06687
 0.3414    288.0  0.62  1.53  1549.57  712.51   1458.  621.  1777.70 1752.59 1758.33 1752.58 0.11346 0.02235
 0 3420    302.4  0.42  1.43  1574.24  730.46   1478.  631.  1873.16 1853.35 1856.59 1852.86 0.09899-0.02472
 0.3426    316.8  0.25  1.28  1600.17  735.54   1503.  643.  1992.62 1980.74 1980.72 1979.24 0.07674-0.07476
 0.3432    331.2  0.12  1.11  1627.72  731.76   1530.  656.  2132.74 2130.51 2126.59 2127.62 0.04431-0.12968
 0.3438    345.6  0.03  0.91  1656.73  720.87   1559.  670.  2287.80 2294.32 2286.47 2290.08 0.00136-0.18351
 0 3444    360.0  0.00  0.71  1487.37  708.92   1587.  683.  2447.00 2459.07 2447.84 2453.86-0.05327-0.23033
 TG=        1586.   1617.           1668.    1487.                709.    691.              694.    683.
TCA=   1587.   1587.   1617.   1674.   1666.   1409.    785.    708.    690.    687.    693.    683.
 TM=   1643.   1672.   1672.   1672.   1672.   1409.    786.    646.    642.    642.    646.    592.
QIN= 383.615 QOUT= 259.704 WRKEXP= 363.320 WRKCMP=-202.966 WRKTOT= 160.354 EFFTOT=   0.418 REFF1=   0.997 REFF2=   0.996
QREGEN=   0.508 PWRHP=  19.470 FREQ=  66.780 WRKLT=  24.848 UTOTAL=     0.000
EN3PM=  6310.710 AVGWSP= 2171.724
QEXPN=  -4.352 QEXPP=   0.134 QHEATN=-373.284 QHEATP=   2.760 QCOOLN=  -4.791 QCOOLP= 201.904 QCOMPN=   0.000 QCOMPP=   2.871
QREGN=-1774.715 QREGP=1775.223 QCNDRI=  5.178 QCNDRO=  5.178
QCNDCL=   1.388 QCNDD=   0.368 QCNDCN=   0.000 TGEXPA=1538.626 TGCMPA= 655.718 QSHTL=   1.939
QINB = 374.742 WRKBAS = 185.202 WALT = 182.192 QOUTB= 199.984 WRKLEX=  19.589 WRKLCM=   5.260 WLEXR=   3.808
WLCMR=   2.608 WLEXE=   8.989 WLCME=   1.275 WRKLR=   6.416 WRKLH=   6.792 WRKLC=   1.377 WRKLE=  10.264 WLALT=  21.838

* CYCLE NO. 24 *
 TIME      ANGLE    REEXP    RECD1    REIH     REOH     RECD2    REIR     REOR     RECD3    REIC     REOC     RECD4     RECMP
 0 0000    360.0    4367.    5293.    8689.   18023.   12117.      43.     195. 113300.   36477.   41650. 265363. 289173.
 0 0006     14.4   38789.   39064.   41402.   48668.   27650.      78.     228. 128422.   40436.   44361. 274889. 294081.
 0 0012     28.8   69964.   69510.   71614.   79639.   43093.     110.     241. 131861.   40759.   43210. 260488. 273441.
 0 0018     43.2   93814.   93204.   96035.  106260.   55154.     130.     230. 122256.   37179.   38141. 223114. 229201.
 0.0024     57.6  108831.  109025.  112581.  122453.   61104.     136.     197. 101161.   30240.   29872. 168017. 167510.
 0 0030     72.0  114024.  115395.  118557.  124500.   60074.     128.     147.   71883.   20974.   19541. 102425.  96200.
 0 0036     86.4  108288.  110273.  111998.  112560.   52731.     108.      87.   38072.   10493.    8299.  33224.  22433.
 0 0042    100.8   92412.   94143.   94107.   89802.   40723.      79.      23.    2924.     694.    2931.  34102.  48140.
 0.0048    115.2   69722.   70678.   69133.   61441.   26547.      46.      39.   32631.   11260.   13899.  96826. 111939.
 0 0054    129.6   43559.   43655.   41006.   31266.   11866.      14.      92.   60872.   20331.   23639. 152090. 167070.
 0 0060    144.0   17063.   16494.   13229.    2824.    1775.      15.     133.   81479.   26950.   31470. 197411. 211830.
 0.0066    158.4    5576.    6581.   10117.   21960.   14092.      40.     164.   95771.   31233.   36711. 229914. 244222.
 0.0072    172.8   24325.   25595.   29581.   42208.   24261.      61.     184. 104363.   33508.   39100. 247052. 262059.
 0 0078    187.2   40225.   41230.   45062.   56681.   31414.      75.     191. 106669.   33822.   38816. 247474. 263366.
 0 0084    201.6   53292.   53948.   56974.   66278.   35786.      83.     188. 103087.   32375.   36447. 232925. 248664.
 0.0090    216.0   63800.   64217.   66163.   72303.   37988.      87.     175.   94597.   29457.   32519. 206543. 220471.
 0 0096    230.4   72147.   72376.   73297.   75987.   38745.      87.     156.   82393.   25414.   27440. 171578. 182058.
 0.0102    244.8   78680.   78720.   78735.   78114.   38614.      86.     131.   67464.   20541.   21512. 130629. 136344.
 0 0108    259.2   83458.   83296.   82487.   78853.   37825.      82.     103.   50352.   15006.   14916.  85334.  85365.
 0 0114    273.6   86114.   85740.   84161.   77806.   36272.      77.      70.   31123.    8850.    7730.  36583.  30397.
 0 0120    288.0   85692.   85105.   82801.   74001.   33521.      69.      32.    9509.    2049.     530.  15385.  28471.
 0.0126    302.4   81258.   80489.   77605.   66934.   29421.      58.      16.   13110.    5172.    8695.  73532.  92641.
 0.0132    316.8   70842.   69935.   66617.   54775.   23123.      42.      51.   37151.   13035.   18149. 133129. 156779.
 0 0138    331.2   52994.   51994.   48372.   36164.   14027.      20.     100.   63755.   21596.   27595. 189179. 215241.
 0.0144    345.6   27435.   26398.   22623.   11007.    2133.       9.     150.   90199.   29781.   35747. 235039. 261207.
 TG=        1586.   1617.           1668.    1487.                709.    691.              694.    683.
TCA=   1587.   1587.   1617.   1674.   1666.   1409.    785.    708.    690.    687.    693.    683.
 TM=   1643.   1672.   1672.   1672.   1672.   1409.    786.    646.    642.    642.    646.    592.
QIN= 383.614 QOUT= 259.727 WRKEXP= 363.322 WRKCMP=-202.968 WRKTOT= 160.354 EFFTOT=   0.418 REFF1=   0.997 REFF2=   0.996
```

```
QREGEN=   0.495 PWRHP=  19.470 FREQ=  66.780 WRKLT=  24.848 UTOTAL=     0.000
EN3PM=  6310 710 AVGWSP= 2171.734
QEXPN=  -4.352 QEXPP=   0.134 QHEATN=-373.283 QHEATP=   2.760 QCOOLN=  -4.789 QCOOLP= 201.925 QCOMPN=   0.000 QCOMPP=   2.871
QREGN=-1774.719 QREGP=1775.215 QCNDRI=  5.178 QCNDRO=  5.178
QCNDCL=   1.388 QCNDD=   0.368 QCNDCN=   0.000 TGEXPA=1538.626 TGCMPA= 655.723 QSHTL=   1.939
QINB = 374 741 WRKBAS = 185.202 WALT = 182.193 QOUTB= 200.008 WRKLEX=  19.589 WRKLCM=   5.260 WLEXR=   3.808
WLCMR=   2.608 WLEXE=   8.989 WLCME=   1.275 WRKLR=   6.416 WRKLH=   6.792 WRKLC=   1.377 WRKLE=  10.264 WLALT=  21.839

< CYCLE NO. 25 *
 TIME     ANGLE    FOEXP    FIHTR    FOHTR    FIREG    FOREG    FICLR    FOCLR    FICMP
 0.0150    360.0-0.00746-0.01062-0.03578-0.05327-0.23033-0.24378-0.29628-0.34836
 0 0156     14.4-0.06709-0.06869-0.09021-0.11060-0.26132-0.27237-0.31499-0.35756
 0 0162     28.8-0.12272-0.12343-0.14399-0.16240-0 26890-0.27658-0.30599-0.33471
 0.0168     43.2-0.16625-0.16688-0.18588-0.19812-0.24990-0.25399-0.26872-0.28162
 0 0174     57.6-0.19347-0.19425-0.20692-0.21164-0.20730-0.20803-0.20854-0.20596
 0 0180     72.0-0.20185-0.20221-0.20437-0.20240-0.14794-0.14580-0.13407-0.11802
 0 0186     86 4-0.18996-0.18935-0.18051-0.17352-0 07952-0.07517-0.05401-0.02739
 0 0192    100.8-0 16030-0.15863-0.14092-0.13060-0.00390-0.00291 0.02461 0.05841
 0 0198    115.2-0.11951-0.11706-0.09387-0.08194 0 06035 0.07035 0.09881 0.13494
 0 0204    129.6-0.07377-0.07090-0.04510-0.03289 0.11694 0.12896 0.16362 0.19968
 0 0210    144.0-0.02856-0.02558-0.00022 0.01133 0.16000 0.17189 0.21519 0.25066
 0 0216    158.4 0.00922 0.01215 0.03931 0.05149 0.19115 0.20171 0.25001 0.28590
 0 0222    172.8 0.03980 0 04292 0.07132 0.08421 0.21058 0.21962 0.26645 0.30362
 0 0228    187.2 0.06517 0.06774 0.09421 0.10744 0.21681 0.22440 0.26502 0.30239
 0 0234    201.6 0.08560 0.08746 0.10948 0.12198 0.21073 0.21682 0.24916 0.28348
 0 0240    216.0 0.10178 0.10305 0.11905 0.12957 0 19441 0.19887 0.22232 0.25009
 0 0246    230 4 0 11457 0.11527 0.12472 0.13231 0.17031 0.17302 0.18733 0.20596
 0 0252    244.8 0.12471 0.12482 0.12773 0.13186 0.14047 0.14132 0.14631 0.15417
 0 0258    259.2 0.13243 0.13190 0.12844 0.12896 0.10597 0.10490 0.10051 0.09669
 0 0264    273.6 0.13723 0.13602 0.12632 0.12331 0.06687 0.06392 0.05046 0.03457
 0.0270    288.0 0.13756 0.13566 0.11981 0.11346 0.02236 0 01781-0.00342-0.03257
 0 0276    302.4 0.13176 0.12926 0.10812 0.09899-0.02472-0.03107-0.06634-0.10687
 0.0282    316.8 0.11625 0.11326 0.08800 0 07674-0.07475-0.08396-0.13317-0.18268
 0 0288    331.2 0.08811 0.08478 0.05689 0.04431-0.12968-0.14189-0.19867-0.25361
 0 0294    345.6 0.04624 0.04274 0.01424 0.00136-0.18351-0.19747-0.25515-0.31130
 TG=        1586.   1617.            1668.   1487.              709.    691.              694.    683.
TGA=   1587.   1587.   1617.   1674.   1666.   1409.    785.    708.    690.    687.    693.    683.
 TM=   1643.   1672.   1672.   1672.   1672.   1409.    786.    646.    642.    642.    646.    592.
QIN= 383.612 QOUT= 259.746 WRKEXP= 363.323 WRKCMP=-202.969 WRKTOT= 160.354 EFFTOT=   0.418 REFF1=   0.997 REFF2=   0.996
QREGEN=   0.482 PWRHP=  19.470 FREQ=  66 780 WRKLT=  24.848 UTOTAL=     0.000
EN3PM=  6310.710 AVGWSP= 2171.742
QEXPN=  -4.352 QEXPP=   0.134 QHEATN=-373.281 QHEATP=   2.760 QCOOLN=  -4.787 QCOOLP= 201.942 QCOMPN=   0.000 QCOMPP=   2.871
QREGN=-1774.724 QREGP=1775.207 QCNDRI=  5.178 QCNDRO=  5.178
QCNDCL=   1.388 QCNDD=   0.368 QCNDCN=   0.000 TGEXPA=1538.627 TGCMPA= 655.727 QSHTL=   1.939
QINB = 374.739 WRKBAS = 185.203 WALT = 182.193 QOUTB= 200.026 WRKLEX=  19.589 WRKLCM=   5.260 WLEXR=   3.808
WLCMR=   2.608 WLEXE=   8 989 WLCME=   1.275 WRKLR=   6.416 WRKLH=   6.792 WRKLC=   1.377 WRKLE=  10.264 WLALT=  21.839


** AVERAGE VALUES OVER LAST 5 CYCLES **

QIN= 383.615 QOUT= 259.694 WRKEXP= 363.319 WRKCMP=-202.965 WRKTOT= 160.354 EFFTOT=   0.418 REFF1=   0.997 REFF2=   0.996
QREGEN=   0.480 PWRHP=  19.470 FREQ=  66.780 WRKLT=  24.848 UTOTAL=     0.000
EN3PM=  6310.710 AVGWSP= 2171.719
QEXPN=  -4.352 QEXPP=   0.134 QHEATN=-373.284 QHEATP=   2.760 QCOOLN=  -4.792 QCOOLP= 201.895 QCOMPN=   0.000 QCOMPP=   2.871
```

```
QREGN=-1774.741 QREGP=1775.221 QCNDRI=  5.178 QCNDRO=  5.178
QCNDCL=   1.388 QCNDD=   0.368 QCNDCN=   0.000 TGEXPA=1538.626 TGCMPA= 655.714 QSHTL=   1.939
QINB = 374 742 WRKBAS = 185.202 WALT = 182.192 QOUTB= 199.974 WRKLEX=  19.589 WRKLCM=   5.260 WLEXR=   3.808
WLCMR=   2.608 WLEXE=   8.989 WLCME=   1.275 WRKLR=   6.416 WRKLH=   6.792 WRKLC=   1.377 WRKLE=  10.264 WLALT=  21.838

** AVG. TEMPS.--LAST 5 CYCLES, AVG. H. T. COEFS. & HEAT FLUXES--LAST CYCLE **

 TGCYC=       1530.   1528.           1524.   1482.            703.    691.            669.    659.
TGACYC=   1539.   1527.   1545.   1543.   1505.   1400.    780.    697.    679.    668.    665.    656.
 TMCYC=   1643.   1672.   1672.   1672.   1672.   1400.    780.    646.    642.    642.    646.    592.
 HACYC=   0.057   0.000   0.808   0.810   0.000   1.923   1.879   0.000   0.622   0.672   0.000   0.075
  HMX=   0.443   0.000   1.413   1.435   0.000   2.950   2.779   0.000   1.027   1.099   0.000   0.245
QOAAVG=    5.65    0.00   69.15   72.89    0.00    4.45    4.38    0.00   22.67   19.22    0.00    5.03
 QOAMX=   22.90    0.00  132.68  128.62    0.00    8.45    8.53    0.00   46.29   59.10    0.00   25.85

** PPESSURE CALCULATIONS--EXPANSION AND COMPRESSION SPACE **

AVGPE=2172.765 AVGPC=2171.588 PEMAX=2758.990 PEMIN=1663.097
PCMAX=2800.018 PCMIN=1632.701
APEMAX=  53.280 APEMIN= 246.240 APCMAX=  54.000 APCMIN= 246.960

** ENGINE POWER AND EFFICIENCY CALCULATIONS **

BASICP=  22.487  FRLOSS=   4.294  BRKP=  15.176  BRKEFF=   0.326

AUXLOS=   2.692 AUXPWR=  12.485 AUXEFF=   0.268

** COOLER AND APPENDIX GAP PUMPING CALCULATIONS **

&CHKPOM
TH2OAV= 585.98948208376
RH2O= 3.0311088482520
RTUBE= 0.27440452269027
QBTUPS= 22.310718811145
W= 0.45779056053055D-02
QHGPS= 15.373266780887
QCGPS= 0.11240588565159
&END
```

TABLE VIII. - SHORT FORM OF OUTPUT DATA
(PRODUCED WHEN IOUT = 1, JIP = 1)

```
** RUN IDENTIFICATION **

READ #123BR,

** CALCULATED CONTROL VOLUME AND ENGINE PARAMETERS, AND INPUT DATA **

&EPARAM
HDEDV= 2.1788355858357
RDEDV= 7.0420962338519
CDEDV= 1.4725243637283
DGAPDV= 0.38090003924925
DHO= 2*2.1650, 3*0.11810, 2 2440, 5*0.27190952380952D-02, 0.22440D01, 3*0.39370D-01
2*0.169260D01, 13*0.0
ACSO= 3.6813379069113, 1.8406689534556, 3*0.98589845512928D-01, 0.39549007266381D01
5*0.22938424214501D01, 0.39549007266381D01, 3*0.23373402598861D0, 0.17530335352219D01
0.35060670704439D01, 13*0.0
AHTO= 2*0.0, 3*11.033826006996, 0.0, 5*1035.9469775373, 0.0, 3*20.945228440128
15*0.0
XLO= 0.0, 0.73098424215499D-01, 3*0.36833333333333D01, 0.12857465588833D0
5*0.3070D0, 0.39343591850981D-01, 3*0.1050D01, 0.52566022354121D0, 14*0.0
VO= 0.0, 0.26910, 3*0.72627852861190, 1.0170, 5*1.4084192467704, 0.31120
3*0.49084145457609, 1.8430, 14*0.0
VCLE= 0.52610003924925
VCLC= 0.17599000392493
CLRLOD= 80.010160020320
HTRLOD= 93.564775613887
RGAREA= 3.9549007266381
AP= 3.6813379069113
AR= 0.17527083646743
APMAR= 3.5060670704439
VHAPGP= 0.38090003924925
VCAPGP= 0.38090003924925D-01
THGP= 1373.6666666667
TCGP= 646.40894661755
QHGPS= 0.0
QCGPS= 0.0
IPUMP= 1
ICOND= 0
&END

** INPUT DATA--ENGINE PARAMETERS **

&ENGINE
EID= -0.47377992506120D28
ETYPE= 1.0
DISPD= 2.1650
DISPRD= 0.47240
DSPGAP= 0.15750D-01
DSPHGT= 3.530
RODL= 3.9370
```

```
RCPANK= 0.78740
E= 0.0
PHASE= 90.0
HTBOD= 0.17720
HTBID= 0.11810
HTBPCN= 18.0
HTBL= 11.050
EHIBL= 9.9130
REGPCN= 2.0
REGID= 2.2440
REGL= 1.5350
RWIRED= 0 19690D-02
FROSTY= 0.580
RMDEN= 0 2820
CPM= 0.110
CTBOD= 0.59060D-01
CTBID= 0.39370D-01
CTBPCN= 384.0
CTBL= 3.150
ECTBL= 2.6460
CNDSS= 0.27780D-02
CPH2O= 1.0
RHOH2O= 62.40
AEFH2O= 5.0
EXPSCL= 0.14520
EXPHDV= 0.26910
HRDV= 1.0170
RCDV= 0 31120
CCMPDV= 1.8430
CMPSCL= 0.13790
CYLORT= 1.360
CYLORM= 1.310
CYLORB= 1.250
CYLDTM= 0.7870
CYLDMB= 0 7870
DSPWTH= 0 750D-01
REGORT= 1.420
REGORM= 1.370
REGORB= 1.30
REGDTM= 0.5940
REGDMB= 0.5940
STROKE= 1.5750
CANOR= 0.0
CANIR= 0.0
CONDTB= 0 0
DFPEQ= 66.670
DFLOSS= 17.1650
DALOSS= 10.060
&END

** INPUT DATA--OPTION SWITCHES AND MULTIPLYING FACTORS **

&STRLNG
```

```
REALGS= 1.0
FACT1= 0.40
FACT2= 10 0
NOCYC= 25
NSTRT= 1
NOEND= 20
MWGAS= 2
RHCFAC= 1.0
HHCFAC= 1.0
CHCFAC= 1.0
IPCV= 0
FMULT= 1.0
FMULTR= 1.0
IMIX= 0
VH2= 0.990
IPUMP= 1
ICOND= 0
IOUT= 1
JIP= 1
IPRINT= 500
ITMPS= 0
MAPLOT= 1
&END

** INPUT DATA--ENGINE OPERATING CONDITIONS **

&INDATA
IDRUN= -641351228, 1081864690, -205334165
P= 2635.5934534073
OMEGA= 66.780
TMEXP= 1643.0
TMHFR= 1672.0
TMHBR= 1672.0
TCYL= 1643 0, 1441.0, 1239.0
TCAN= 1191.0, 999.0
TRO= 1472.0
TR1= 1214.0
TR2= 956.0
GPMH2O= 13.630
TH2OIN= 580.10
&END

** METAL TEMPERATURES FOR CONDUCTION CALCULATIONS **
&INTEMP
TCYL= 1643.0, 1441.0, 1239.0
TCAN= 1191.0, 999.0
TRO= 1472.0
TR1= 1214.0
TR2= 956.0
&END

QIN= 378.131 QOUT= 260.212 WRKEXP= 358.513 WRKCMP=-202.013 WRKTOT= 156.500 EFFTOT=   0.414 REFF1=   0.997 REFF2=   0.995
```

```
QREGEN=  -0.658 PWRHP=  19.002 FREQ=  66.780 WRKLT=  24.634 UTOTAL=      0.000
EN3PM=  6310 710 AVGWSP= 2157.025
QEXPN=  -4.589 QEXPP=   0.125 QHEATN=-386.310 QHEATP=   2.176 QCOOLN=  -4.616 QCOOLP= 197.033 QCOMPN=    0.000 QCOMPP=    2.795
QREGN=-1761 219 QREGP=1760.561 QCNDRI=  5.178 QCNDRO=  5.178
QCNDCL=   1.388 QCNDD=   0.365 QCNDCN=   0.000 TGEXPA=1532.013 TGCMPA= 654.260 QSHTL=   1.939
QINB = 388 598 WRKBAS = 181.134 WALT = 178.041 QOUTB= 195.212 WRKLEX=  19.338 WRKLCM=   5.296 WLEXR=   3.753
WLCMR=   2.635 WLEXE=   8.881 WLCME=   1.278 WRKLR=   6.388 WRKLH=   6.704 WRKLC=   1.383 WRKLE=  10.159 WLALT=  21.541


** LAST CYCLE **

QIN= 378.131 QOUT= 260.212 WRKEXP= 358.513 WRKCMP=-202.013 WRKTOT= 156.500 EFFTOT=   0.414 REFF1=   0.997 REFF2=   0.995
QREGEN=  -0.658 PWRHP=  19.002 FREQ=  66.780 WRKLT=  24.634 UTOTAL=      0.000
EN3PM=  6310.710 AVGWSP= 2157.025
QEXPN=  -4.589 QEXPP=   0.125 QHEATN=-386.310 QHEATP=   2.176 QCOOLN=  -4.616 QCOOLP= 197.033 QCOMPN=    0.000 QCOMPP=    2.795
QREGN=-1761.219 QREGP=1760.561 QCNDRI=  5.178 QCNDRO=  5.178
QCNDCL=   1.388 QCNDD=   0.365 QCNDCN=   0.000 TGEXPA=1532.013 TGCMPA= 654.260 QSHTL=   1.939
QINB = 388.598 WRKBAS = 181.134 WALT = 178.041 QOUTB= 195.212 WRKLEX=  19.338 WRKLCM=   5.296 WLEXR=   3.753
WLCMR=   2.635 WLEXE=   8.881 WLCME=   1.278 WRKLR=   6.388 WRKLH=   6.704 WRKLC=   1.383 WRKLE=  10.159 WLALT=  21.541


** AVERAGE VALUES OVER LAST 5 CYCLES **

QIN= 378 176 QOUT= 260.410 WRKEXP= 358.522 WRKCMP=-202.027 WRKTOT= 156.495 EFFTOT=   0.414 REFF1=   0.997 REFF2=   0.995
QREGEN=  -0.648 PWRHP=  19.001 FREQ=  66.780 WRKLT=  24.635 UTOTAL=      0.000
EN3PM=  6310.710 AVGWSP= 2157.094
QEXPN=  -4.590 QEXPP=   0.125 QHEATN=-386.352 QHEATP=   2.172 QCOOLN=  -4.599 QCOOLP= 197.216 QCOMPN=    0.000 QCOMPP=    2.797
QREGN=-1761.119 QREGP=1760.471 QCNDRI=  5.178 QCNDRO=  5.178
QCNDCL=   1.388 QCNDD=   0.365 QCNDCN=   0.000 TGEXPA=1531.996 TGCMPA= 654.312 QSHTL=   1.939
QINB = 388 644 WRKBAS = 181.130 WALT = 178.036 QOUTB= 195.414 WRKLEX=  19.338 WRKLCM=   5.296 WLEXR=   3.753
WLCMR=   2.635 WLEXE=   8.881 WLCME=   1.278 WRKLR=   6.388 WRKLH=   6.704 WRKLC=   1.383 WRKLE=  10.159 WLALT=  21.541


** AVG  TEMPS.--LAST 5 CYCLES, AVG. H. T. COEFS. & HEAT FLUXES--LAST CYCLE **

 TGCYC=         1523.   1522.           1519.   1477.           701.    689.            668.    658.
TGACYC=   1532.   1521.   1540.   1538.   1500.   1395.   778.    695.    678.    667.    663.    654.
  TMCYC=  1643.   1672.   1672.   1672.   1672.   1395.   778.    646.    641.    641.    646.    592.
 HACYC=   0.056   0.000   0.805   0.807   0.000   1.915   1.878   0.000   0.622   0.671   0.000   0.075
   HMX=  0 447   0.000   1.415   1.439   0.000   2.957   2.778   0.000   1.025   1.096   0.000   0.242
QOAAVG=    5.93    0.00   71.82   74.96    0.00    4.41    4.36    0.00   22.19   18.66    0.00    4.90
 QOAMX=   25.24    0.00  137.42  131.73    0.00    8.43    8.53    0.00   45.16   57.51    0.00   25.05


** PRESSURE CALCULATIONS--EXPANSION AND COMPRESSION SPACE **

AVGPE=2158.025 AVGPC=2156.872 PEMAX=2735.649 PEMIN=1653.789
PCMAX=2777.046 PCMIN=1623.724
APEMAX=  52.560 APEMIN= 246.240 APCMAX=  53.280 APCMIN= 246.240


** ENGINE POWER AND EFFICIENCY CALCULATIONS **
```

```
BASICP=  21.993  FRLOSS=   4.272  BRKP=  14.730  BRKEFF=   0.321

AUXLOS=   2.686 AUXPWR=  12.045 AUXEFF=   0.262

** COOLER AND APPENDIX GAP PUMPING CALCULATIONS **

&CHKROM
TH2OAV= 586.01304542543
RH2O= 3.0307937576335
RTUBE= 0.27440452269027
QBTUPS= 22.399982193349
W= 0.45617150644983D-02
QHGPS= 15.544561636230
QCGPS= 0.10697760560297
&END

QIN= 383.612 QOUT= 259.746 WRKEXP= 363.323 WRKCMP=-202.969 WRKTOT= 160.354 EFFTOT=   0.418 REFF1=   0.997 REFF2=   0.996
QREGEN=   0.482 PWRHP=  19.470 FREQ=  66.780 WRKLT=  24.848 UTOTAL=     0.000
EN3PM=  6310.710 AVGWSP= 2171.742
QEXPN=  -4.352 QEXPP=   0.134 QHEATN=-373.281 QHEATP=   2.760 QCOOLN=  -4.787 QCOOLP= 201.942 QCOMPN=   0.000 QCOMPP=   2.871
QREGN=-1774.724 QREGP=1775.207 QCNDRI=  5.178 QCNDRO=  5.178
QCNDCL=   1.388 QCNDD=   0.368 QCNDCN=   0.000 TGEXPA=1538.627 TGCMPA= 655.727 QSHTL=   1.939
QINB = 374.739 WRKBAS = 185.203 WALT = 182.193 QOUTB= 200.026 WRKLEX=  19.589 WRKLCM=   5.260 WLEXR=   3.808
WLCMR=   2.608 WLEXE=   8.989 WLCME=   1.275 WRKLR=   6.416 WRKLH=   6.792 WRKLC=   1.377 WRKLE=  10.264 WLALT=  21.839

** LAST CYCLE **

QIN= 383.612 QOUT= 259.746 WRKEXP= 363.323 WRKCMP=-202.969 WRKTOT= 160.354 EFFTOT=   0.418 REFF1=   0.997 REFF2=   0.996
QREGEN=   0.482 PWRHP=  19.470 FREQ=  66.780 WRKLT=  24.848 UTOTAL=     0.000
EN3PM=  6310.710 AVGWSP= 2171.742
QEXPN=  -4.352 QEXPP=   0.134 QHEATN=-373.281 QHEATP=   2.760 QCOOLN=  -4.787 QCOOLP= 201.942 QCOMPN=   0.000 QCOMPP=   2.871
QREGN=-1774.724 QREGP=1775.207 QCNDRI=  5.178 QCNDRO=  5.178
QCNDCL=   1.388 QCNDD=   0.368 QCNDCN=   0.000 TGEXPA=1538.627 TGCMPA= 655.727 QSHTL=   1.939
QINB = 374.739 WRKBAS = 185.203 WALT = 182.193 QOUTB= 200.026 WRKLEX=  19.589 WRKLCM=   5.260 WLEXR=   3.808
WLCMR=   2.608 WLEXE=   8.989 WLCME=   1.275 WRKLR=   6.416 WRKLH=   6.792 WRKLC=   1.377 WRKLE=  10.264 WLALT=  21.839

** AVERAGE VALUES OVER LAST 5 CYCLES **

QIN= 383.615 QOUT= 259.694 WRKEXP= 363.319 WRKCMP=-202.965 WRKTOT= 160.354 EFFTOT=   0.418 REFF1=   0.997 REFF2=   0.996
QREGEN=   0.480 PWRHP=  19.470 FREQ=  66.780 WRKLT=  24.848 UTOTAL=     0.000
EN3PM=  6310.710 AVGWSP= 2171.719
QEXPN=  -4.352 QEXPP=   0.134 QHEATN=-373.284 QHEATP=   2.760 QCOOLN=  -4.792 QCOOLP= 201.895 QCOMPN=   0.000 QCOMPP=   2.871
QREGN=-1774.741 QREGP=1775.221 QCNDRI=  5.178 QCNDRO=  5.178
QCNDCL=   1.388 QCNDD=   0.368 QCNDCN=   0.000 TGEXPA=1538.626 TGCMPA= 655.714 QSHTL=   1.939
QINB = 374.742 WRKBAS = 185.202 WALT = 182.192 QOUTB= 199.974 WRKLEX=  19.589 WRKLCM=   5.260 WLEXR=   3.808
WLCMR=   2.608 WLEXE=   8.989 WLCME=   1.275 WRKLR=   6.416 WRKLH=   6.792 WRKLC=   1.377 WRKLE=  10.264 WLALT=  21.838

** AVG. TEMPS.--LAST 5 CYCLES, AVG. H. T. COEFS. & HEAT FLUXES--LAST CYCLE **
```

```
 TGCYC=        1530.   1528.              1524.   1482.              703.    691.               669.    659.
TGACYC=   1539.   1527.   1545.   1543.   1505.   1400.    780.    697.    679.    668.    665.    656.
 TMCYC=   1643.   1672.   1672.   1672.   1672.   1400.    780.    646.    642.    642.    646.    592.
 HACYC=   0.057   0.000   0.808   0.810   0.000   1.923   1.879   0.000   0.622   0.672   0.000   0.075
   HMX=  0.443   0.000   1.413   1.435   0.000   2.950   2.779   0.000   1.027   1.099   0.000   0.245
QOAAVG=    5.65    0 00   69.15   72.89    0.00    4.45    4.38    0.00   22.67   19 22    0.00    5.03
 QOAMX=   22.90    0.00  132.68  128.62    0.00    8.45    8.53    0.00   46.29   59.10    0.00   25.85


** PRESSURE CALCULATIONS--EXPANSION AND COMPRESSION SPACE **

AVGPE=2172.765 AVGPC=2171.588 PEMAX=2758.990 PEMIN=1663.097
PCMAX=2800.018 PCMIN=1632.701
APEMAX=  53.280 APEMIN= 246.240 APCMAX=  54.000 APCMIN= 246.960


** ENGINE POWER AND EFFICIENCY CALCULATIONS **

BASICP=  22.487  FRLOSS=   4.294  BRKP=  15.176  BRKEFF=   0.326

AUXLOS=   2.692 AUXPWR=  12.485 AUXEFF=   0.268


** COOLER AND APPENDIX GAP PUMPING CALCULATIONS **

&CHKROM
TH2OAV= 585 98948208376
RH2O= 3.0311088482520
RTUBE= 0.27440452269027
QBTUPS= 22.310718811145
W= 0.45779056053055D-02
QHGPS= 15.373266780887
QCGPS= 0.11240588565159
&END
```

TABLE IX. - FINAL SUMMARY PRINTOUT

```
ENGINE OPERATING CONDITIONS
--------------------------------------------------------------------------
 ENGINE SPEED                           4006.8 RPM          66.78 HZ
 MEAN PRESSURE                          2171.7 PSI          14.98 MPA
 HEATER TUBE OUTSIDE TEMPERATURE        1672.0 R      1212.3 F        928.9 K         655.7 C
 COOLANT INLET TEMPERATURE               580.1 R       120.4 F        322.3 K          49.1 C
 RESULTANT INSIDE COOLER TUBE TEMP.      641.9 R       182.2 F        356.6 K          83.5 C

ENGINE PERFORMANCE SUMMARY
---------------------------------------------------------------------------
 BRAKE POWER-1 CYLINDER                 12.485 HP        9.310 KW       102.824 FT-LBF/CYCLE
            -4 CYLINDERS                49.939 HP       37.239 KW       411.296 FT-LBF/CYCLE
 BRAKE EFFICIENCY                        0.268
 INDICATED POWER-1 CYLINDER             19.470 HP       14.519 KW       160.355 FT-LBF/CYCLE
                -4 CYLINDERS            77.880 HP       58.075 KW       641.418 FT-LBF/CYCLE
 INDICATED EFFICIENCY                    0.418
 HEAT RATE TO ENGINE-1 CYLINDER         46.577 HP       34.733 KW       383.612 FT-LBF/CYCLE
                    -4 CYLINDERS       186.310 HP      138.931 KW      1534.447 FT-LBF/CYCLE
 HEAT RATE FROM ENGINE
  HEAT RATE TO COOLANT-1 CYLINDER       31.538 HP       23.518 KW       259.746 FT-LBF/CYCLE
                      -4 CYLINDERS     126.151 HP       94.071 KW      1038.982 FT-LBF/CYCLE
  AUXILIARY LOSS (4 CYLINDERS)          10.767 HP        8.029 KW        88.677 FT-LBF/CYCLE
  TOTAL RATE (4 CYLINDERS)             136.918 HP      102.100 KW      1127.659 FT-LBF/CYCLE

 % ERROR IN ENERGY BALANCE               0.294 %

 MECHANICAL LOSS (4 CYLINDERS)          17.174 HP       12.807 KW       141.445 FT-LBF/CYCLE

 FLOW FRICTION LOSS (4 CYLINDERS)       12.068 HP        8.999 KW        99.393 FT-LBF/CYCLE


INDICATED WORK PER CYCLE SUMMARY (1 CYLINDER)------------------------------------------------
 EXPANSION SPACE (WRKEXP)              363.323 FT-LBF/CYCLE
 COMPRESSION SPACE (WRKCMP)           -202.969 FT-LBF/CYCLE
 NET (WRKTOT)                                              160.355 FT-LBF/CYCLE


HEAT FLOW SUMMARY (1 CYLINDER)---------------------------------------------------------------
HEAT RATE TO ENGINE
 EXPANSION SPACE HEAT RATE
  METAL TO GAS (QEXPN)                  -4.352 FT-LBF/CYCLE
  GAS TO METAL (QEXPP)                   0.134 FT-LBF/CYCLE
  NET (QEXP)                                                -4.218 FT-LBF/CYCLE
 HEATER HEAT RATE
  METAL TO GAS (QHEATN)               -373.281 FT-LBF/CYCLE
  GAS TO METAL (QHEATP)                  2.760 FT-LBG/CYCLE
  NET (QHEATR)                                            -370.521 FT-LBF/CYCLE
 CONDUCTION LOSSES
  THROUGH REGENERATOR HOUSING(QCNDRI)    5.178 FT-LBF/CYCLE
  THROUGH CYLINDER HOUSING(QCNDCL)       1.388 FT-LBF/CYCLE
  DIRECTLY THROUGH PISTON(QCNDD)         0.368 FT-LBF/CYCLE
  SHUTTLE LOSS VIA PISTON (QSHTL)        1.939 FT-LBF/CYCLE
  NET (QCNDTI)                                              -8.873 FT-LBF/CYCLE
NET HEAT RATE TO ENGINE (QEIN)                                                -383.612 FT-LBF/CYCLE
(- SIGN MEANS FLOW INTO ENGINE)

HEAT RATE FROM ENGINE
```

```
  COOLER HEAT RATE
   GAS TO METAL (QCOOLP)                     201.942 FT-LBF/CYCLE
   METAL TO GAS (QCOOLN)                      -4.787 FT-LBF/CYCLE
   NET (QCOOLR)                                                   197.155 FT-LBF/CYCLE
  COMPRESSION SPACE HEAT RATE
   GAS TO METAL (QCOMPP)                       2.871 FT-LBF/CYCLE
   METAL TO GAS (QCOMPN)                       0.000 FT-LBF/CYCLE
   NET (QCOMP)                                                      2.871 FT-LBF/CYCLE
  APPENDIX GAP PUMPING LOSSES
   HOT GAP (QHGPS)                            15.373 FT-LBF/CYCLE
   COLD GAP (QCGPS)                            0.112 FT-LBF/CYCLE
   NET (QAPGAP)                                                    15.486 FT-LBF/CYCLE
  CONDUCTION LOSSES (QCNDTO)                                        8.873 FT-LBF/CYCLE
 TOTAL HEAT FLOW TO COOLANT,EXCLUDING MECHANICAL LOSSES                              224.384 FT-LBF/CYCLE
  MECHANICAL LOSSES (1 CYLINDER)                                   35.361 FT-LBF/CYCLE

 NET HEAT RATE TO COOLANT(QCLOUT)                                                    259.746 FT-LBF/CYCLE
  AUXILIARY LOSSES (1 CYLINDER)                                    22.169 FT-LBF/CYCLE
 NET HEAT RATE FROM ENGINE (QEOUT)                                                   281.915 FT-LBF/CYCLE


 REGENERATOR HEAT FLOW
  METAL TO GAS (QREGN)                    -1774.724 FT-LBF/CYCLE
  GAS TO METAL (QREGP)                     1775.206 FT-LBF/CYCLE
  NET (QREGEN)                                                      0.482 FT-LBF/CYCLE
  % ERROR REG. ENERGY BALANCE(PREGER)                               0.027 %
  (QREGEN/(MINIMUM OF ABS. VALUE OF QREGN & QREGP))


 REGENERATOR EFFECTIVENESS CALCULATION (BASED ON ENTHALPY FLOW PER CYLINDER)--------------------------
  NET ENTHALPY FLOW REG. TO HTR.(ENFRTH)                         3284.703 FT-LBF/CYCLE
  NET ENTHALPY FLOW HTR. TO REG.(ENFHTR)                         3294.560 FT-LBF/CYCLE
  REG. EFFECT.(REFF1=ENFRTH/ENFHTR)                                 0.9970
  NET ENTHALPY FLOW CLR. TO REG.(ENFCTR)                         2108.668 FT-LBF/CYCLE
  NET ENTHALPY FLOW REG. TO CLR.(ENFRTC)                         2117.549 FT-LBF/CYCLE
  REG. EFFECT.(REFF2=ENFCTR/ENFRTC)                                 0.9958


 PRESSURE DROP LOSS SUMMARY (PER CYLINDER)--------------------------------------------------------------
  HEATER (WRKLH)                                                    6.792 FT-LBF/CYCLE
  REGENERATOR
   HOT SIDE (WLEXR)                            3.808 FT-LBF/CYCLE
   COLD SIDE (WLCMR)                           2.608 FT-LBF/CYCLE
   NET (WRKLR)                                                      6.416 FT-LBF/CYCLE
  COOLER (WRKLC)                                                    1.377 FT-LBF/CYCLE
  CONNECTING DUCTS (END EFFECTS)
   HOT SIDE (WLEXE)                            8.989 FT-LBF/CYCLE
   COLD SIDE (WLCME)                           1.275 FT-LBF/CYCLE
   NET (WRKLE)                                                     10.264 FT-LBF/CYCLE
  NET HOT SIDE (WRKLEX)                                                      19.589 FT-LBF/CYCLE
  NET COLD SIDE (WRKLCM)                                                      5.260 FT-LBF/CYCLE
  NET ENGINE PRESSURE DROP LOSS (WRKLT)                                                24.848 FT-LBF/CYCLE

 PRESSURES---------------------------------------------------------------------------------------------
  EXPANSION SPACE
   MAXIMUM (PEMAX)                          2759.0 PSI          19.028 MPA
   MINIMUM (PEMIN)                          1663.1 PSI          11.470 MPA
   MEAN (AVGPE)                             2172.8 PSI          14.985 MPA
   RATIO (PEMAX/PEMIN)                        1.659
  COMPRESSION SPACE
```

TABEL VI. - SYMBOL DEFINITIONS FOR ENGINE
OPERATING CONDITIONS
(NAMELIST /INDATA/)

SYMBOL	DEFINITION
IDRUN	Alphanumeric run identifier
P	Mean pressure, lbf/in^2, (MPa)
OMEGA	Engine frequency, hz
TMEXP	Expansion space wall temperature, °R (K)
TMHFR	Outside temperature of front row (flame side) portion of heater tubes, °R (K)
TMHBR	Outside temperature of back row portion of heater tubes, °R (K)
TCYL(1)	Cylinder housing temperature, top, °R (K)
TCYL(2)	Cylinder housing temperature, middle, °R (K)
TCYL(3)	Cylinder housing temperature, bottom, °R (K)
TCAN(1)	Insulation container temperature, top, °R (K)
TCAN(2)	Insulation container temperature, bottom, °R (K)
TR0	Regenerator housing temperature, top, °R (K)
TR1	Regenerator housing temperature, middle, °R (K)
TR2	Regenerator housing temperature, bottom, °R (K)
GPMH2O	Cooling water flow rate per cylinder, gal./min (liter/sec)
TH2OIN	Cooling water inlet temperature, °R (K)

TABLE V. - SYMBOL DEFINITIONS (AND TEST CASE SETTINGS) FOR MODEL OPTION SWITCHES AND MULTIPLYING FACTORS (NAMELIST /STRLNG/)

SYMBOL	SETTING	DEFINITION
REALGS	1.	Use real gas equation of state
	0.	Use ideal gas equation of state
FACT1	0.4	Empirical factors used in regenerator matrix temperature
FACT2	10.0	convergence procedure
NOCYC	25	Number of engine cycles to be calculated (per pass)
NSTRT	1	Cycle number at which regenerator matrix temperature convergence procedure begins
NOEND	20	Cycle number at which regenerator matrix temperature convergence procedure ends
MWGAS	2	Use hydrogen working gas
	4	Use helium working gas
RHCFAC	1.	Regenerator heat transfer coefficient multiplying factor
HHCFAC	1.	Heater heat transfer coefficient multiplying factor
CHCFAC	1.	Cooler heat transfer coefficient multiplying factor
IPCV	0	Make second pass through calculations to improve prediction of effect of pressure drop
	1	Eliminate second pass
FMULT	1.0	Overall pressure drop multiplying factor
FMULTR	1.0	Regenerator pressure drop multiplying factor
IMIX	1	Use mixture of hydrogen and carbon dioxide working gas
	0	Pure hydrogen or helium working gas
VH2	0.99	Volume fraction of hydrogen in hydrogen-carbon dioxide mixture (used only if IMIX=1)
IPUMP	1	Calculate pumping loss due to piston-cylinder gap
	0	Omit pumping loss calculation
ICOND	1	Calculate cylinder and regenerator housing temperatures from TM(1), TM(4) and TH2OIN (Input hot and cold end temperatures)
	0	Use the specified input values of the cylinder and regenerator housing temperatures for conduction calculations
IOUT	1	Write out Table VII or VIII data
	0	Don't write out Table VII or VIII data
JIP	0	Write out Table VII data if IOUT=1
	1	Write out Table VIII data if IOUT=1
IPRINT	500	Number of time steps between variable printouts in Table VII data
ITMPS	1	Write out instantaneous gas temperatures at each time step in Table VII (for debugging)
	0	Don't write out instantaneous gas temperatures at each time step
MAPLOT	1	Store variables for plotting
	0	Don't store variables for plotting

MAXIMUM (PCMAX)	2800.0 PSI	19.310 MPA
MINIMUM (PCMIN)	1632.7 PSI	11.260 MPA
MEAN (AVGPC)	2171.6 PSI	14.976 MPA
RATIO (PCMAX/PCMIN)	1.715	

MEAN PRESSURE, CTR. OF REG. (AVGWSP)	2171.7 PSI	14.978 MPA

AVERAGE PRESSURE RATIO ((PEMAX+PCMAX)/(PEMIN+PCMIN)) 1.687

TABLE X. - READ/WRITE UNIT NUMBERS USED FOR INPUT/OUTPUT

	INPUT/OUTPUT STATEMENT	SUBROUTINE	UNIT #	INPUT/OUTPUT DATA (TEST CASE)
1.	READ	ROMBC	4	TABLE II
2.	READ	ROMBC	5	TABLE IV
3.	WRITE	ROMBC,CYCL	6	TABLE VII (if IOUT=1 and JIP=0)
4.	WRITE	CYCL	16	TABLE IX
5.	WRITE	ROMBC	13	BINARY OUTPUT (if MAPLOT=1)

TABLE XI. - ARRAYS SET VIA EQUIVALENCE STATEMENT IN SUBROUTINE ROMBC

COMMON/RESET/ EQUIVALENCE ARRAY FOR COMMON/RESET/	WRKLT, WRKLR, WRKLE, WRKLTO, WRKLRO, WRKLHO, WRKLEO, SET(1), SET(2), SET(3), SET(4), SET(5), SET(6), SET(7) VARIABLES
COMMON/TIMEO/	WEPO, WCPO, WEPEO, WCPCO, WEDURO, WCDURO, WEDUHO, WO(1), WO(2), WO(3), WO(4), WO(5), WO(6), WO(7), WCDUCO, WEDUEO, WCDUCO, WEALTO, WTPCO WO(8), WO(9), WO(10), WO(11), WO(12)
COMMON/TIME1/	WEP1, WCP1, WEPE1, WCPC1, WEDUR1, WCDUR1, WEDUH1, W1(1), W1(2), W1(3), W1(4), W1(5), W1(6), W1(7). WCDUC1, WEDUE1, WCDUC1, WEALT1, WTPC1 WI(8), WI(9), WI(10), WI(11), WI(12)
COMMON/TIME2/	WEP2, WCP2, WEPE2, WCPC2, WEDUR2, WCDUR2, WEDUH2, W2(1), W2(2), W2(3), W2(4), W2(5), W2(6), W2(7), WCDUC2, WEDUE2, WCDUC2, WEALT2, WTPC2 W2(8), W2(9), W2(10), W2(11), W2(12)
COMMON/PSET/	PRIN, PROUT, PEXP, PCMP, PEDUR, PCDUR, PEDUH, PCDUC, PS(1), PS(2), PS(3), PS(4), PS(5), PS(6), PS(7), PS(8), PEDUE, PCDUE, PEALT P(9) P(10) P(11)
COMMON/ASET/	AEP, ACP, AE, AC, AEDUR, ACDUR, AEDUH, ACDUC, AS(1), AS(2), AS(3), AS(4), AS(5), AS(6), AS(7), AS(8), AEDUE, ACDUE, AEALT, ATPC AS(9), AS(10), AS(11), AS(12)

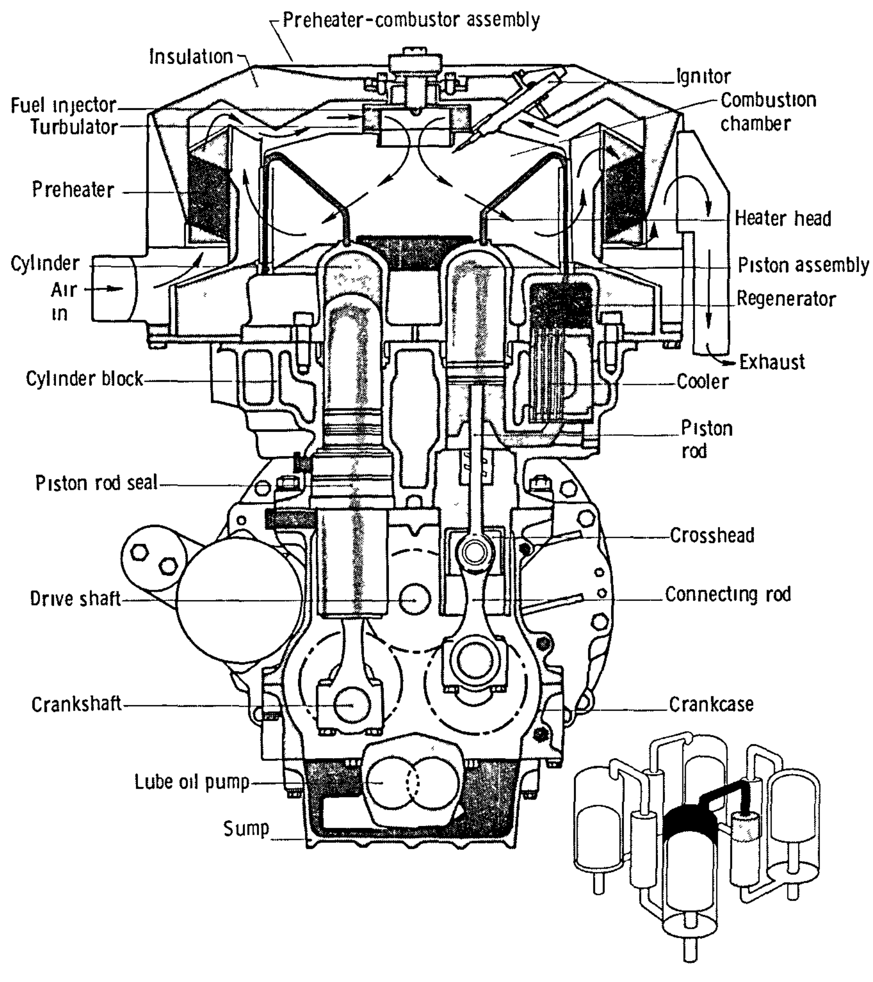


Figure 1. - P40 Stirling engine cross section.

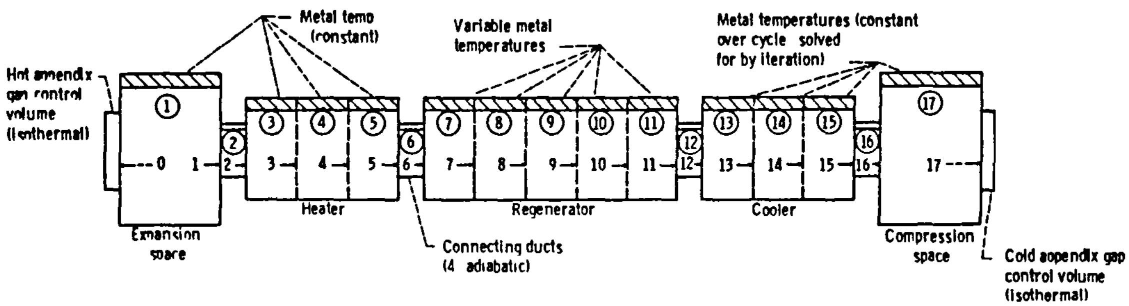


Figure 2 - Control volumes as set-up for test case

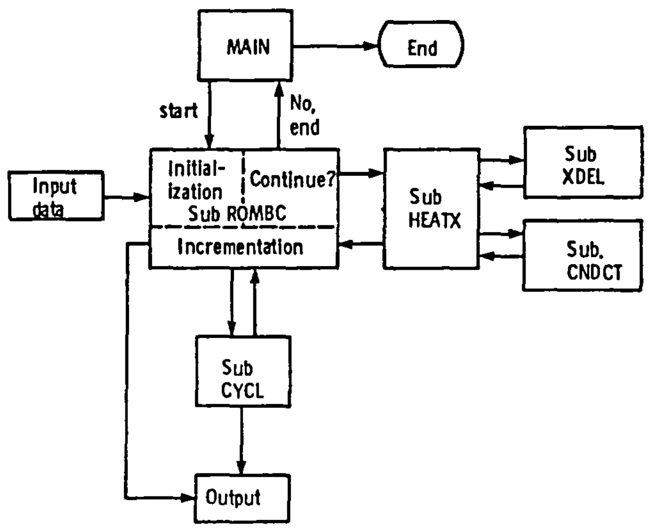


Figure 3 - Overall simulation structure

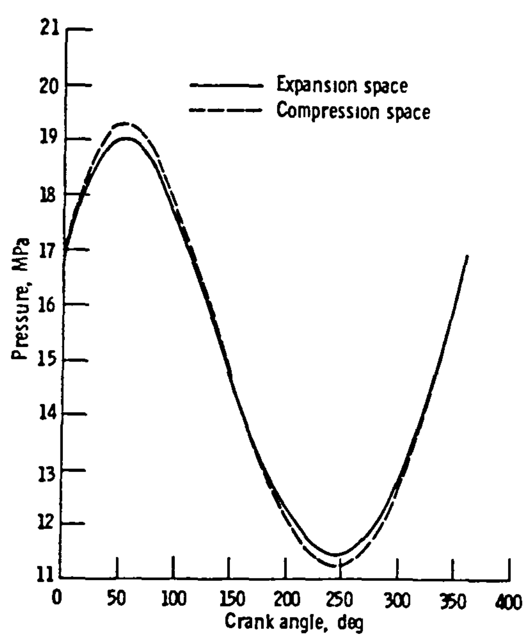


Figure 4. - Pressure vs crank angle

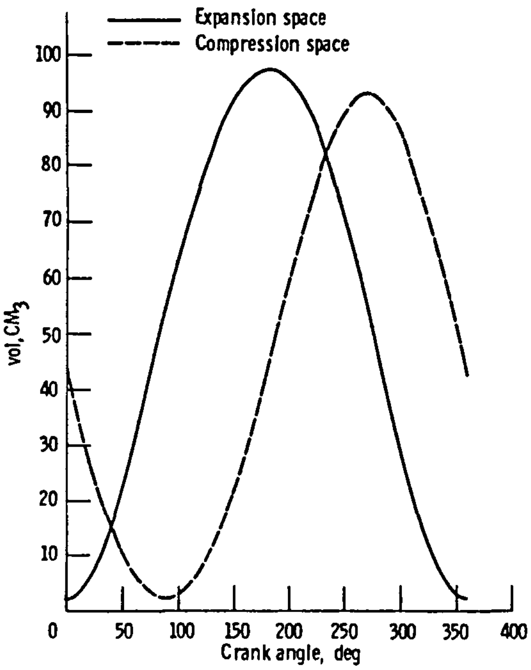


Figure 5 - vol vs crank angle

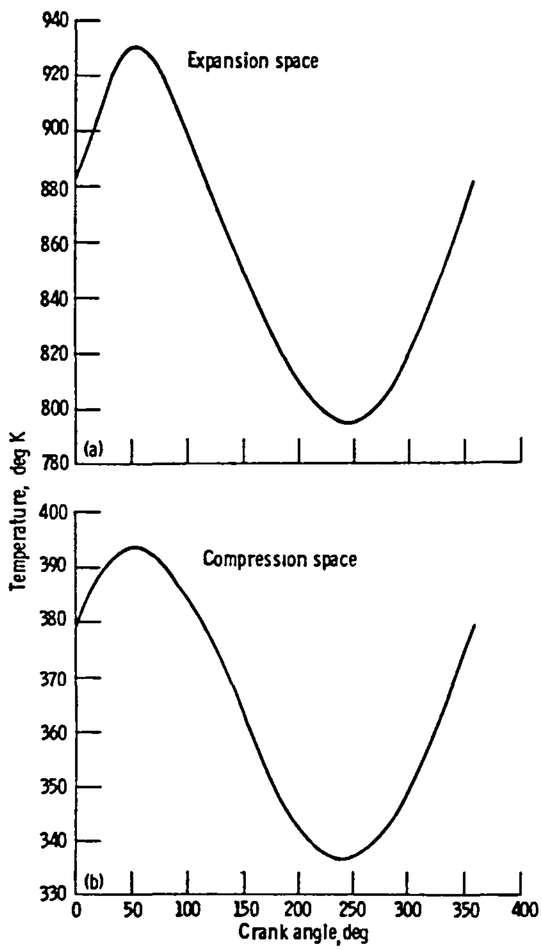


Figure 6. - Gas temperature vs crank angle

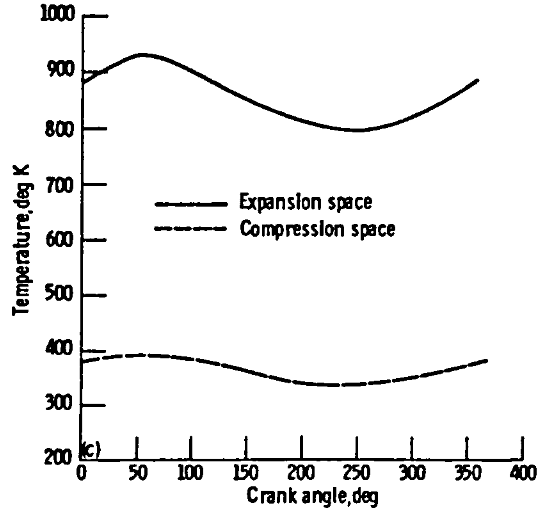


Figure 6. - Concluded.

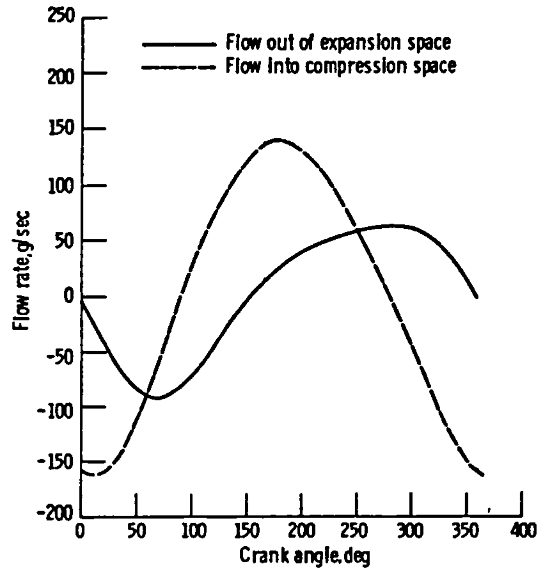


Figure 7. - Gas flow rate vs crank angle.

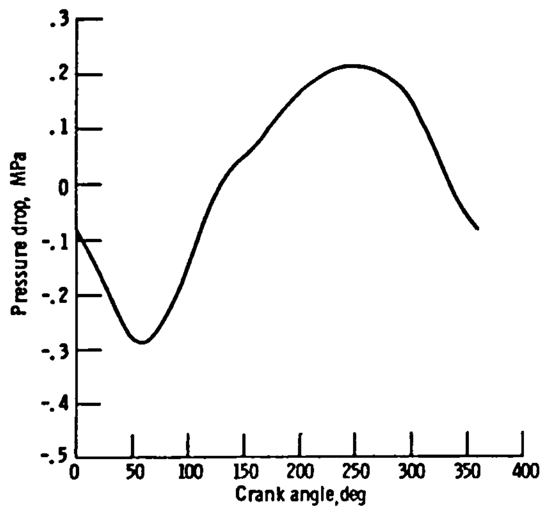


Figure 8. - Engine pressure drop vs crank angle

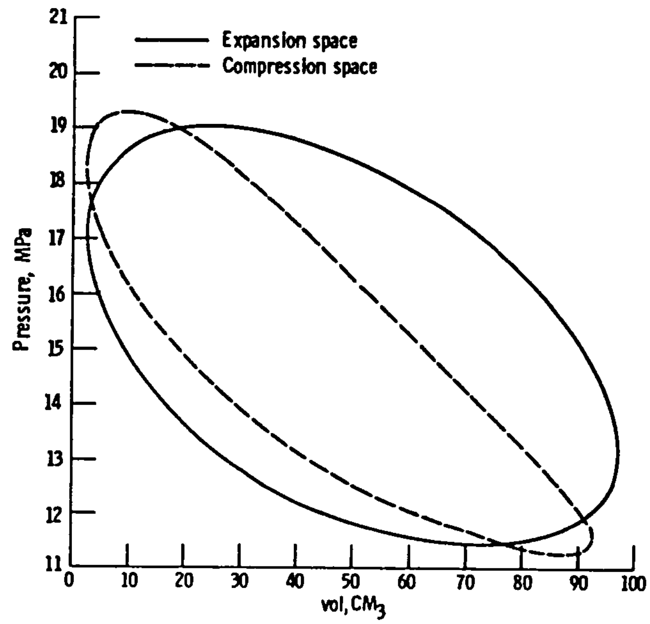


Figure 9 - P-V diagrams

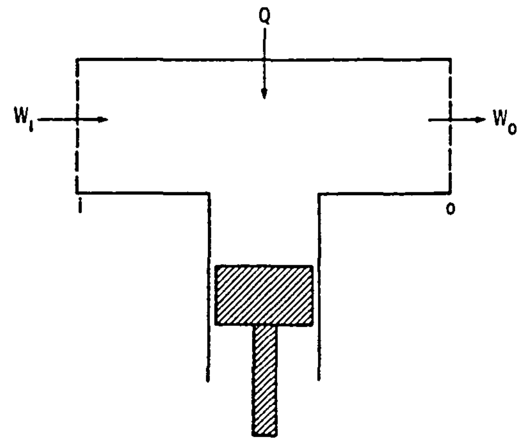
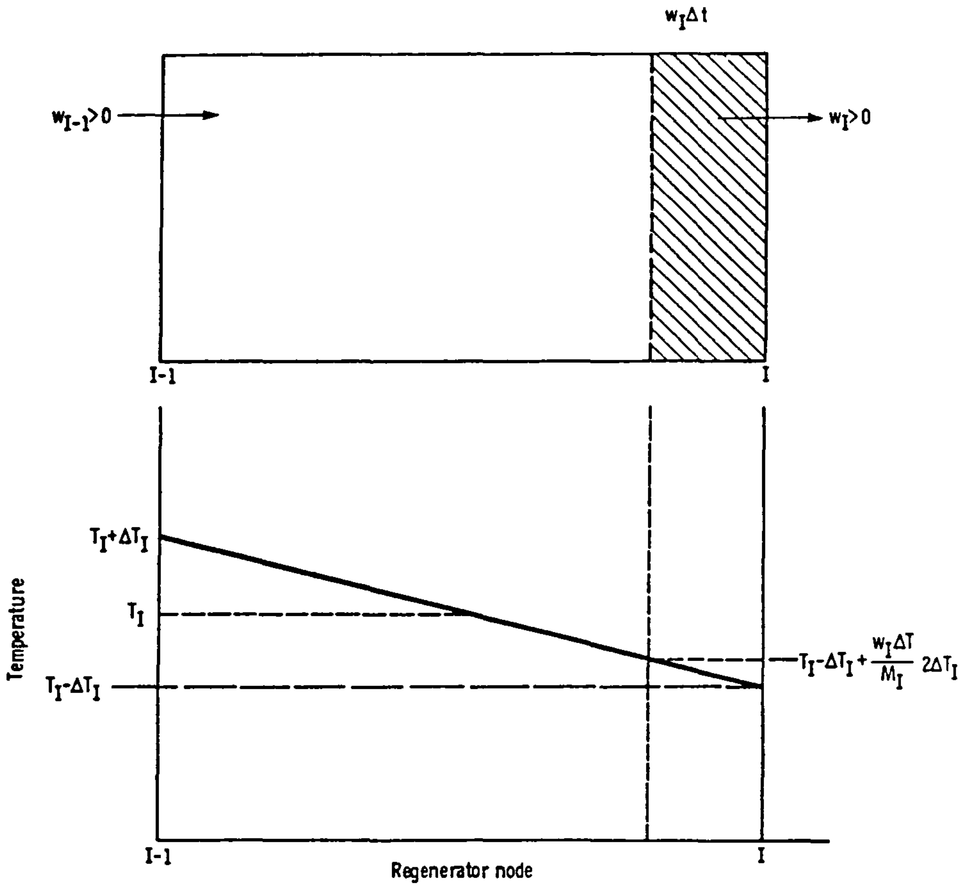


Figure 10 - Generalized control volume

Inputs, preliminary calculations, initializations

1. Update time and crank angle, ROMBC
2. Update expansion and compression space volumes, ROMBC
3. Update thermal conductivity and viscosity for gas control volumes, HEATX
4. Updat pressure level, HEATX
5. Update gas specific heats, HEATX
6. Update gas temperatures for effect of change in specific heats, HEATX
7. Update gas temperatures for effect of change in pressure, HEATX
8. Update mass distribution, HEATX
9. Update flow rates, HEATX
10. Update gas temperatures for effect of flow between control volumes, HEATX
11. Update heat transfer coefficients, HEATX
12. Update gas temperatures for effect of metal-gas heat transfer, HEATX
13. Update regenerator matrix temperatures, HEATX
14. Update friction factors and pressure drops for each control volume, XDEL
15. Update conduction and shuttle losses once each cycle, CNDCT
16. Sum up heat transfers for each component, HEATX
17. Calculate work and sum vp for cycle, ROMBC
18. Is cycle complete? (No — return to 1; Yes — continue)
19. Revise regenerator matrix temperatures?, ROMBC (Yes, Make revision; No)
20. Calculate indicated power and efficiency, CYCL
21. Calculate mechanical friction losses, CYCL
22. Calculate auxiliary losses and brake power and efficiency, CYCL (if specified number of cycles has been completed)
23. Revise cooler tube temperatures?, ROMBC (Yes, Make revision; No)
24. Have specified no of cycles been completed?, ROMBC (No — return to 1; Yes — continue)
25. Is this the second pass through nocyc cycles?, ROMBC (No — 26; Yes — continue)
26. Reset time=0 and make 2nd pass using Δp Information from 1st pass (return to 1)
27. Write summary of predictions and terminate run

Figure 11. - Outline of calculation procedures



(a) Sample regenerator control volume

(b) Control-volume temperature profile.

Figure 12 - Sample regenerator control volume and temperature profile

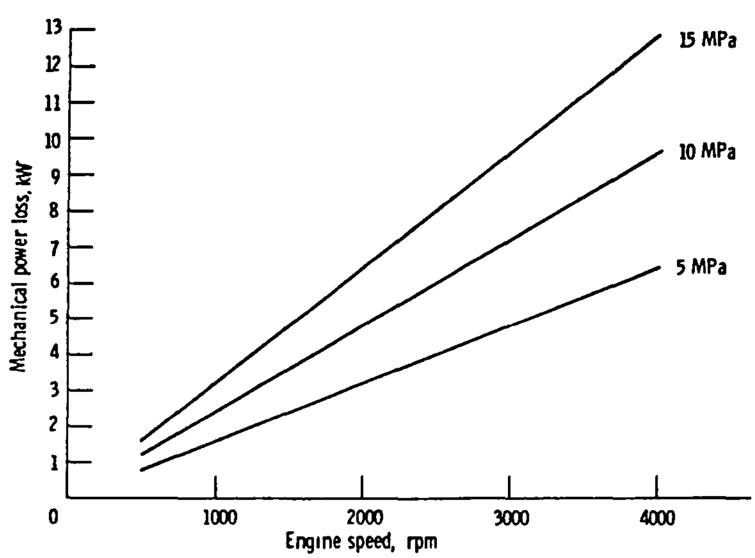


Figure 13 - Mechanical power loss as a function of engine speed and mean pressure

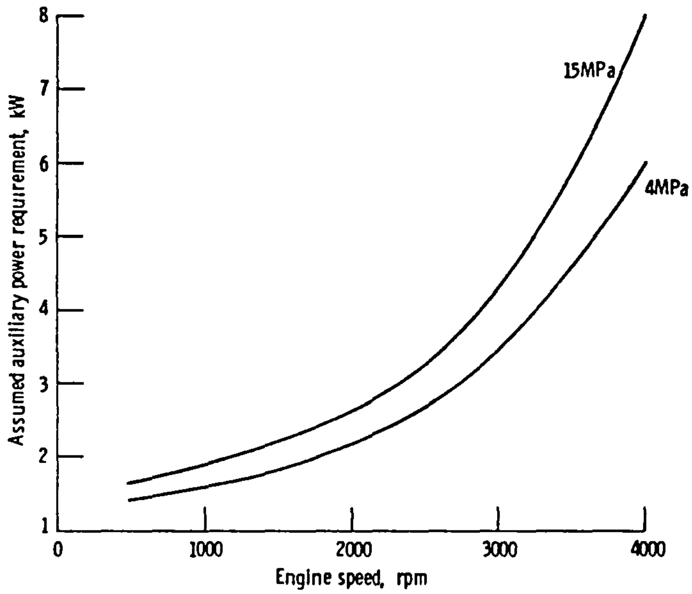


Figure 14 - Auxiliary power requirement as a function of engine speed and mean pressure

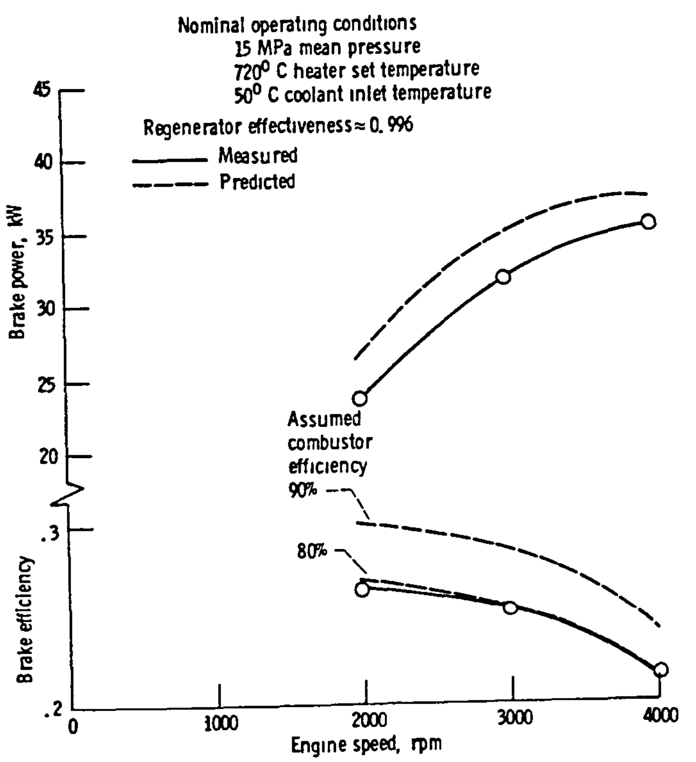


Figure 15 - P-40 brake power and efficiency as functions of engine speed.

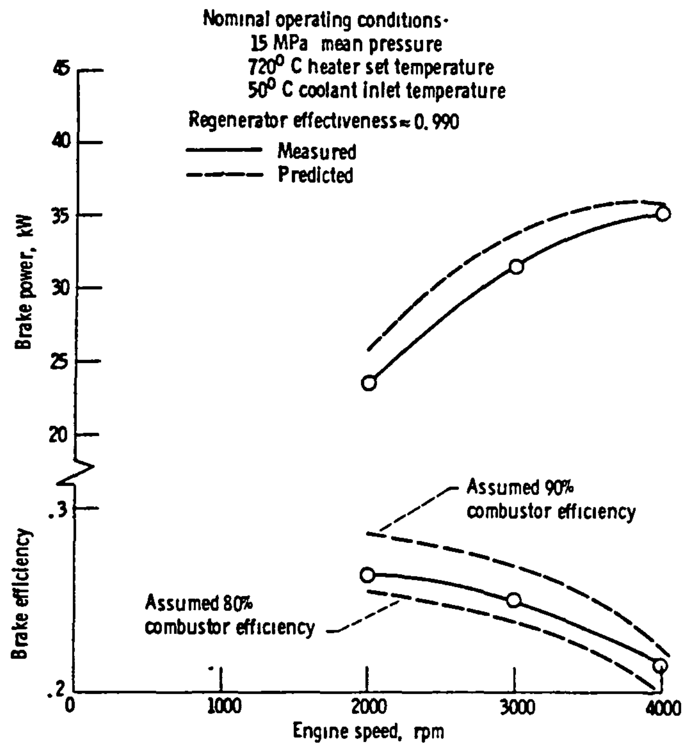


Figure 16 - P-40 brake power and efficiency as functions of engine speed

1 Report No NASA TM-82960	2 Government Accession No	3 Recipient's Catalog No

4 Title and Subtitle COMPUTER PROGRAM FOR STIRLING ENGINE PERFORMANCE CALCULATIONS	5 Report Date January 1983
	6 Performing Organization Code 778-35-03
7 Author(s) Roy C. Tew, Jr.	8 Performing Organization Report No E-1377
	10 Work Unit No
9 Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135	11 Contract or Grant No
	13 Type of Report and Period Covered Technical Memorandum
12 Sponsoring Agency Name and Address U. S. Department of Energy Office of Vehicle and Engine R&D Washington, D.C. 20545	14 Sponsoring Agency ~~Code~~Report No. DOE/NASA/51040-42

15 Supplementary Notes

Final report. Prepared under Interagency Agreement DE-AI01-77CS51040.

16 Abstract

To support the development of the Stirling engine as a possible alternative to the automobile spark-ignition engine, the thermodynamic characteristics of the Stirling engine were analyzed and modeled on a computer. The computer model is documented. The documentation includes a user's manual, symbols list, a test case, comparison of model predictions with test results, and a description of the analytical equations used in the model.

17 Key Words (Suggested by Author(s)) Stirling engine Computer model Stirling cycle	18 Distribution Statement Unclassified - unlimited STAR Category 85 DOE Category UC-96

19 Security Classif (of this report) Unclassified	20 Security Classif (of this page) Unclassified	21 No of Pages	22 Price*

* For sale by the National Technical Information Service, Springfield Virginia 22161

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