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A Computer Simulation of the Transient Response of a 4 Cylinder Stirling Engine with Burner and Air Preheater in a Vehicle


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Martini Engineering

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Lewis Research Center
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for
U.S. DEPARTMENT OF ENERGY
Conservation and Solar Energy
Office of Transportation Programs
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1.0 ABSTRACT

A series of computer programs are presented with full documentation which simulate the transient behavior of a modern 4 cylinder Siemens arrangement Stirling engine with burner and air preheater. Cold start, cranking, idling, acceleration through 3 gear changes and steady speed operation are simulated. Sample results and complete operating instructions are given. A full source code listing of all programs are included.

Reasonable results are obtained but the program has not been validated.
2.0 INTRODUCTION

This report presents the complete results of the work done under contract DEN 3-226 by Martini Engineering for NASA-Lewis on the DOE-sponsored Automotive Stirling Engine Program.

In brief, this work consists of preparation of a series of computer programs which simulate the transient operation of a 4 cylinder, double acting Stirling engine like the United Stirling P-40 or P-75 engine. Since the dimensions of these machines are proprietary, the computer program is set up using the General Motors 4L23 engine for which there is complete information.

The boundaries of the simulation, that is, what is evaluated and what is not, is given in Section 3. Section 4 describes the programs in mathematical terms and justifies the equations that are used. After each small section of explanation, a copy of the part of the computer program it explains is given.

Section 5 gives the full listings for two programs. CNTLA is the pre-program to prepare the data file and allow change in input data from the console. CNTLB is the main program that calculates and displays engine operation during the simulation.

Section 6 gives the program users manual which is written to be complete by itself and contains all the operator needs to apply the programs.

Section 7 presents a sample solution using the final program.

Section 8 summarizes what was learned in trying to construct a rapid but accurate simulation program for use in studying control schemes.
3.0 PROBLEM DEFINITION

The computer program presented and explained herein is to simulate the operation of a Stirling engine powered vehicle. The simulation starts with engine and vehicle stopped and at a given ambient temperature. Figure 3.1 shows a schematic of one part of the engine giving the names of the engine parts. The burner is started at full fuel flow. Air flow is made a specified fraction of fuel flow to supply 10% excess air. The flame heats the heater tubes and then heats a plate type counter flow air preheater. One burner is assumed to heat all heater tubes because this is what the United Stirling engines have. It does not matter that the 4L23 uses 4 separate burners. Transient heat up of both engine and air preheater is simulated. A separate preliminary computer program, WARM, was written to separately investigate this part of the engine (see Appendix A). Gas transit times in the burner are neglected. Heat transfer rates are computed from standard correlations. The heater tubes are regarded as one node but the length of the air preheater is divided into as many as 20 nodes. WARM was used to determine the largest reasonable time step as far as the burner and air preheater are concerned. WARM also was used to determine the smallest number of nodes the air preheater can be divided into and still retain adequate accuracy. The computation method found to be accurate by the use of WARM is incorporated into the main program.

Longitudinal heat conduction in the air preheater is simulated. Fuel is assumed not to be preheated. However, the flow rates of the air and flue gas are realistic as is the heat capacity. The thermal heat conductivity and the viscosity of the flue gas is assumed to be the same as air.

The temperature of the gas heater tubes is regulated by proportional control for the engine cycle with a set point and a proportional band. At first, heat is removed from the heater tubes only by conduction to the other metallic parts of the engine. Since this is the chief heat leak when the engine is stopped, other heat conduction paths, like through the insulation, are ignored since these would be much less.

After the burner has been on for a specified time period, the engine is cranked for a specified time period with a specified torque. At the same time a timing valve opens up to add gas to each working space in turn during the time that that particular working space is expanding. Under the influence of these two forces, the engine accelerates to idling speed that is specified. As the idling speed is reached, the engine pressure is adjusted to keep this idling speed.

Next, the clutch is engaged. To simulate this, the ratio of meters traveled by the vehicle per engine revolution changes smoothly over a short time from zero to a new specified value. Provision is made for the gear ratio to change smoothly as two higher vehicle speeds are reached to simulate gear changes in a normal automobile. At the same time the required vehicle speed is put on a ramp to the cruise speed at the end of a specific acceleration time. Gas is added to each cylinder in turn as long as the vehicle speed falls short of the required vehicle speed for that time. Control is by proportional band operating on the flow resistance between the high pressure reservoir and each of the working gas spaces in turn when the vehicle speed
Figure 3.1. Schematic of Engine Simulator (one of 4 cylinders).
is less than the scheduled speed. If the vehicle speed is more than the scheduled speed, then the flow resistance is between each one of the working spaces in turn and the low pressure reservoir.

At the end of the acceleration phase the pressure in the engine is adjusted by proportional control to keep the vehicle going as close as possible to the specified cruise speed. In order to check the calculation method, the time for cruise should be long enough so that the engine and vehicle attain steady state operation. Only at this point can calculated power output and efficiency be possibly compared with validated power output and efficiency data from the literature.

The above describes a simple driving cycle. Of course, more complicated cycles can be traced by changing the program. Also, more complicated control schemes than simple proportional control can be incorporated.

This section has described the problem in qualitative terms to describe in a non-technical way what is being attempted to be calculated. Now Section 4 will present the equations used in the solution and justify them.
4.0 MATHEMATICAL METHOD OF SOLUTION

This section presents the equations used in the analysis and justifies them.

During the development of this program the burner, heater tubes and air preheater were evaluated separately to determine how many nodes there need be in the air preheater and what time step is needed to adequately simulate this part of the machine. (See Appendix A.) Once these values were determined, the computational part of the program was incorporated into the main program. The burner and air preheater will be discussed in its proper order in the main program.

The main program has been divided into two parts because of memory limitation of the Altos computer used by Martini Engineering to write the program. The first part, CNTLA, allows any input parameter to be changed and then intermediate results are calculated. The parameters needed for the main calculation are filed. Then the main program, CNTLB, is brought in. The intermediate results are read in and the simulation proceeds.

Directions for use of the program and how to change input conditions are given in Section 6.

4.1 CNTLA

The flow diagram is given in Figure 4.1. The base case is recorded in data statements. Any input value can be changed by keying in the input number, a space and then a new value with a decimal point. See Section 6 for additional directions. The new input value is read in from the console as QQ and then is given the proper identity.

The input numbers were assigned as the program grew. Therefore, Section 6 gives the identity of the input numbers and what the base case values are. One table gives them in numerical order. The other gives them organized by operating condition and dimensions for the different parts of the machine. For the software available to the Altos computer for high speed computation, only real numbers in fixed point format (no integers) can be read out of the file FORT10.DAT.

The complete listing of CNTLA.FOR is given in Section 5.

4.2 CNTLB

CNTLB does all the computations. Figure 4.2 gives the overall flow chart for this program. The input data are read in from the file. The output conditions are set. Values are initialized that could not be conveniently done in CNTLA. Then if the graphic option is selected, the borders and the schedule of temperature pressures, engine speeds and vehicle speeds are displayed.

Next the engine and vehicle control subprogram is put all in one place so far as possible so that changes can be made more easily. This program increments the time and keeps track of the driving cycle schedule. It calls in the other elements of the computational part of the program as needed. These computational parts need not be subroutines since the return point is
Figure 4.1. Flow Chart for CNIL (numbers refer to line number for listing in Section 5)
Figure 4.2. Overall Flow Chart for CNTLE (numbers refer to line numbers from listing in Sections 5 and throughout the rest of Section 4.1).
always the same. At first only the burner and heat conduction subprogram is used. Then when the engine starts rotating, the engine torque and internal heat transfer subprogram is also used.

If the total time set for the solution is not exceeded, the program repeats starting with the engine and vehicle control. If time is complete, the program stops and a brief summary is printed out. The full listings of both CNTLB and CNTLA are given in Section 5. In this section CNTLB is explained fully. The full program is divided into small sections according to the flow chart of Figure 4.2. For clarity, each small section of explanation is followed by the part of the program it explains.

4.2.1 Read Transfer File (Lines 1 to 67)

Besides comments about purpose of program and dimension and type and data statements, the transfer file FORT10.DAT is read from the disc. This read statement must be exactly parallel to the write statement in CNTLA. Symbols are defined in CNTLA (see page 73).

```
1: C **********PROGRAM CNTLB. FOR**********
2: C WRITTEN BY MARTINI ENGINEERING UNDER CONTRACT NUMBER
3: C DEN-226 FOR NASA-LEWIS UNDER THE DOE ADVANCED AUTOMOTIVE
4: C PROPULSION PROGRAM. CNTLB READS IN THE INPUT DATA FILE
5: C GENERATED IN CNTLA AND CALCULATES AND DISPLAYS RESULTS.
6: C CNTLB CALCULATES THE TRANSIENT PERFORMANCE OF A 4 CYLINDER
7: C DOUBLE ACTING STIRLING ENGINE WITH TUBULAR HEAT EXCHANGERS
8: C AND POROUS REGENERATOR CONNECTED TO A VEHICLE THROUGH A GEAR BOX.
9: C THE RESIDENT DRIVING CYCLE CONSISTS OF HEATUP, CRANKING, IDLE,
10: C ACCELERATION FROM ZERO TO CRUSE SPEED AND HOLD THAT SPEED.
11: C SECOND AND THIRD GEAR CHANGES ARE SPECIFIED BASED UPON VEHICLE
12: C SPEED. GEAR CHANGE IS LINEAR WITH A SPECIFIED TIME.
13: C CNTLA USES AS A BASE CASE THE DIMENSIONS OF THE 4L23 ENGINE.
14: C CNTLB ADJUSTS THE TIME STEP SO THAT THE ANGLE INCREMENT IS
15: C BETWEEN 7 AND 30 DEGREES. THE PROGRAM HAS NO LIMIT TO FLOW
16: C ACROSS GAS NODES OR CHANGE IN GAS INVENTORY. CONTROL IS BY
17: C CHANGE IN GAS INVENTORY.
18:  C
19:  C ****** START OF PROGRAM ******
20:  DIMENSION :X(4), IPV(2, 4), JPV(2, 4),
21:  1 P2(4),P3(4, 8),P4(4),N(4),EP(4),TO(4),VHA(2, 4),VCA(2, 4),
22:  2 VT(2, 4),XX(4),
23:  3 P1(4),CVM(8, 4),TG(A(2, 8, 4),
24:  4 OHI(4),TIA(4),TIN(10),EX(8),TOU(10),TM(6, 4),EY(8),KME(8),
25:  5 CM(8),THA(8, 4),
26:  6 CRM(5),
27:  DIMENSION TM(6, 4),W(2, 8, 4),CVG(8, 4),
28:  FEAL LC,ETF,H,KH,MIN,HT,R,L,N,ME,KAP,NG1
29:  FEAL LHH,LMH,WFG,LFH,MIP1,LMH,MIV,LMM,M2,MF
30:  FEAL NTM,NTC,NS,NE,NTC,NTM,TG1,NO,HAP,LFH,FM,KNK,KNM
31:  C DATA CONSTANTS
32:  DATA PI4,P1,P2,RAD,P,R= 7854.2,14159.1,57000.0,0.017453,8.314,
33:  DATA JCF,CFG,5.1 05.1 20,
34:  C++++++ READ TRANSFER FILE FROM DISK
35:  2004 FORMAT*9999X
```
4.2.2 Initialize Values (Lines 68-129)

Although most initial values are in the transfer file, it is more convenient to initialize some values in CNTLB. Also since integers cannot be read out of the transfer file due to limitations in the software available, integer values, like N and J, must be made at this point.

68: C*****INITIALIZE VALUES
69: C ORGANIZE TIMES FOR OPERATING CYCLE
70: TT=0.
71: T11=THU+TCR
72: T12=T11+TID
73: T13=T12+TAC
74: C BURNER INITIALIZATION
75: N=NO
76: NO2=N/2
77: DO 200 I=1,N
78: TOUT(I)=T1
79: TIN(I)=T1
80: EY(I)=T1
81: EX(I)=T1
82: TIN(N+1)=T1
83: TA=T1
84: TD=THMG-TWI
85: FLAME=T1
86: TOUT(N+1)=T1
87: CFL=1000.
88: CFH=0.
89: CFF=0
90: C INITIALIZE CUMULATIVE HEAT INPUT AND METAL TEMPS
91: DO 198 I=1,4
92: TM(1,I)=T1
93: TM(2,I)=T1
94: TM(3,I)=T1
95: TM(4,I)=T1
96: TM(5,I)=(TWI+T1)/2.
97: TM(6,I)=TWI
98: M(I)=0.0
99: 198 OHI(I)=0.
100: C SET PRINTOUT OPTION
101: J=G2
102: C INITIALIZE VEHICLE INERTIA
103: VIN=0.0
104: C INITIALIZE ENGINE AND VEHICLE SPEED
105: OMEG=0.0
106: SPV1=0.0
107: SPVD=0.0
108: C INITIALIZE WORKING TIME STEP
109: DDT=DT
110: C INITIALIZE TORQUES
111: TQS=0.0
112: TQV=0.0
113: TNET=0.0
114: C INITIALIZE ENGINE ANGLES
115: EARAD=0.0
116: REV=0.0
117: NER=0
118: NGC=-1
119: MIR1=0.
120: RGE=0.
121: C INITIALIZE ENGINE PRESSURE
122: DO 950 I=1,4
123: 950 P1(I)=PRL
124: C INITIALIZE FLAG TO CALCULATE CONDITIONS AT CRANKING
125: IG2=0
126: C INITIALIZE OUTPUT FLAGS
127: PDF=0.0
128: GDF=0.0
129: GDI=TOTT/1024.

11
4.2.3 **Draw Graphic Frames** (Lines 130-212)

The ADM-3 terminal with the Retrographics package can have two output overlaid on the screen at the same time, a graphic output and an alphanumeric output. The graphic output, if it is used, cannot easily be turned off. The alphanumeric output to the screen can be turned off so just the graphic display is visible. It is much easier to understand what is going on with the graphic display. In the case where the graphic display is not used, the output will be stored in a file which may be read back and possibly plotted off line.

The contract requires that the main program, CNTLB, should run without manual intervention during program execution. Therefore, the decisions on how the results of CNTLB are read out are changeable in CNTLA and are fed to CNTLB in the transfer file.

The flag Q1 must be 1.0 if graphic output is to be used. At this point the outline of the graphic display and the schedule of how the driving cycle should go are displayed on the screen. Figure 4.3 shows how the screen is divided up. The retrographics modification to the ADM-3A terminal is capable of displaying 250 points vertically and 512 points horizontally. However, the package is compatible with Tektronix Plot 10 software which has 780 points vertically and 1024 points horizontally. These latter numbers are used to specify location. The subroutine VECTOR draws a line on the screen (see Appendix C).

The arrangement evolved as experience was gained with the solution. Space for the four working space pressure-volume (PV) diagrams was particularly useful in observing what is going on with the solution.

```
130: C******** DRAW GRAPHIC FRAME IF OPTION IS ON
131: C GRAPHIC FRAME
132: IF(Q1-1.00)156,157,158
133: C DRAW OUTLINE
134: 157 CALL CLEAR
135: 11=0
136: J1=0
137: I2=1023
138: J2=0
139: CALL VECTOR(I1, J1, I2, J2)
140: I1=I2=1023
141: J1=779
142: CALL VECTOR(I2, J2, I1, J1)
143: I2=0
144: J2=779
145: CALL VECTOR(I1, J1, I2, J2)
146: I1=0
147: J1=0
148: CALL VECTOR(I2, J2, I1, J1)
149: I1=700
150: J1=0
151: I2=700
152: J2=779
153: CALL VECTOR(I1, J1, I2, J2)
154: C DIVIDE INTO 4 LAYERS LEFT SIDE
```
155: \( I_1 = 0 \)
156: \( J_1 = 629 \)
157: \( I_2 = 700 \)
158: \( J_2 = 629 \)
159: CALL VECTOR \((I_1, J_1, I_2, J_2)\)
160: \( J_1 = 479 \)
161: \( J_2 = 479 \)
162: CALL VECTOR \((I_1, J_1, I_2, J_2)\)
163: C DIVIDE INTO FOUR LAYERS, RIGHT SIDE
164: \( I_1 = 700 \)
165: \( J_1 = 190 \)
166: \( I_2 = 1023 \)
167: \( J_2 = 190 \)
168: CALL VECTOR \((I_1, J_1, I_2, J_2)\)
169: \( J_1 = 380 \)
170: \( J_2 = 380 \)
171: CALL VECTOR \((I_1, J_1, I_2, J_2)\)
172: \( J_1 = 570 \)
173: \( J_2 = 570 \)
174: CALL VECTOR \((I_1, J_1, I_2, J_2)\)
175: C DRAW SCHEDULED VEHICLE SPEED
176: \( I_1 = 0 \)
177: \( J_1 = 632 \)
178: \( I_2 = T_{I2}/T_{TOT}*700 \)
179: \( J_2 = 632 \)
180: CALL VECTOR \((I_1, J_1, I_2, J_2)\)
181: \( I_1 = T_{I3}/T_{TOT}*700 \)
182: \( J_1 = 776 \)
183: CALL VECTOR \((I_2, J_2, I_1, J_1)\)
184: \( I_2 = 700 \)
185: \( J_2 = 776 \)
186: CALL VECTOR \((I_1, J_1, I_2, J_2)\)
187: C DRAW SCHEDULED ENGINE SPEED
188: \( I_1 = 0 \)
189: \( J_1 = 482 \)
190: \( I_2 = T_{H}/T_{TOT}*700 \)
191: \( J_2 = 482 \)
192: CALL VECTOR \((I_1, J_1, I_2, J_2)\)
193: \( I_1 = T_{I2}/T_{TOT}*700 \)
194: \( J_1 = 554 \)
195: \( I_2 = T_{I2}/T_{TOT}*700 \)
196: \( J_2 = 554 \)
197: CALL VECTOR \((I_1, J_1, I_2, J_2)\)
198: C DRAW HOT METAL GOAL TICK (THMG)
199: \( I_1 = 0 \)
200: \( J_1 = 200 \)
201: \( I_2 = 10 \)
202: \( J_2 = 200 \)
203: CALL VECTOR \((I_1, J_1, I_2, J_2)\)
204: C DRAW COOLING WATER TEMP TICK (TWH)
205: \( J_1 = 10 \)
206: \( J_2 = 10 \)
207: CALL VECTOR \((I_1, J_1, I_2, J_2)\)
208: C CALCULATE DISPLAY PARAMETERS
209: \( P_{DIFF} = P_{RH} \)
210: \( X_{LOW} = V_{TD} + V_{HD} + V_{CD} \)
211: \( X_{DV} = (A_{CY} + B_{CY}) * R_{C2} \)
212: 158 CONTINUE
Figure 4.3. Graphic Display Scheme.
4.2.4 Write Unified Printout (Lines 213-229)

The unified printout is placed first in the main loop of the program so that the initial conditions can be displayed. The readout may either be to the screen (Q2 = 5.0) or to the printer (Q2 = 2.0). This option is changed from CNTLA. Then in Line 101 of CNTLB the integer J is set from the real value Q2. The format of the readout is nine columns but not all are filled. The key to the readout is given in the Program Users Manual (Section 6).

Note that this printout is optional. It is enabled when Q3 = 1.0. This flag can be changed from CNTLA. If the graphic readout gives all the information desired, then it greatly speeds up the calculation by having the printout infrequently.

The value TREP can be set from CNTLA to control the repetition time for this printout.

```
134: C*****WRITE UNIFIED PRINTOUT--RETURN POINT FOR MAIN LOOP
214: 401   IF(Q3-1.0)390,402,390
215: 402   IF(TIM-FGF)390,391,391
216: 391   POF=POF+TREP
217:     WRITE(J,8025)TIM,CFF,REV,OMEG,SPV1,SPVD,DDT
218: 8025   FORMAT(6F8.2, F8.5, 2FB.2)
219:     WRITE(J,8022)TIN(1),TIN(2),TIN(3),TIN(4),TIN(5),TIN(6),TIN(7),
220:     TIN(8),TIN(9)
221:     WRITE(J,8022)EX(1),EX(2),EX(3),EX(4),EX(5),EX(6),EX(7),
222:     EX(8),FLAME
223:     WRITE(J,8022)TOU(1),TOU(2),TOU(3),TOU(4),TOU(5),TOU(6),TOU(7),
224:     TOU(8),TOU(9)
225:     DO 10 I=1,4
226: 10    WRITE(J,8022)TM(1,I),TM(2,I),TM(3,I),TM(4,I),TM(5,I),PI(I),
227:     M(I),VT(1,I)
228: 8022   FORMAT(9(F8.2))
229:     WRITE(J,8022)TNET,TQS,TQV,VIN,MIR1,ROE
```
4.2.5 **Display Graphic Data** (Lines 230-290)(Optional)

The display offers a fast and comprehensible way of showing what is going on during the solution. To speed the solution, the display does not print every time step. The total time, TOTT, is divided by 1024, the number of horizontal addresses for plotting to give the graphic display interval, GDI, in seconds. (See line 129.) Therefore, the display programming from line 233 to 277 only is called upon 1024 times during the solution at a regular time interval. There could be 1024 different points if a Tektronix terminal were used. With the ADM-3 Retrographics package used in development of this program, 512 horizontal points are plotable. Therefore, two dots are possible in the vertical direction for every plotable point in the horizontal direction.

The following displays are shown:

A. From the beginning
   1. current fuel flow rate (over full height of display)
   2. average heater metal temperature
   3. flue gas leaving heater and entering preheater
   4. flue gas leaving preheater
   5. average of metal node 1 (around hot spaces)
   6. average of metal node 4 (at the hot end of the regenerators)
   7. average of metal node 5 (at the middle of the regenerators)

B. After engine starts to be cranked (see line 269)
   8. engine speed
   9. vehicle speed

The above displays are plotted 1024 times during the solution or twice for every displayable point using the Retrographics package.

```
230:  C******DISPLAY GRAPHIC DATA, PART 1
231:  390  IF(G1-1)20, 21, 20
232:  C CHECK TO SEE IF PLOTTING SHOULD BE DONE
233:  21  IF(TIM-GDF)20, 21, 20
234:  393  GDF=GDF+GDI
235:  C SHOW FUEL FLOW RATE
236:  I1=TIM/TOTT*700
237:  J1=CF/FFF*777
238:  CALL POINT(I1, J1)
239:  C SHOW AVERAGE HEATER TEMP.
240:  J1=(TA-TWI)/TD+190+10
241:  CALL POINT(I1, J1)
242:  C SHOW FLUE GAS TEMP. ENTERING PREHEATER
243:  J1=(TOU(N+I)-TWI)/TD+190+10
244:  CALL POINT(I1, J1)
245:  C SHOW FLUE GAS TEMP. LEAVING PREHEATER
246:  J1=(TOU(1)-TWI)/TD+190+10
247:  CALL POINT(I1, J1)
248:  C SHOW AVE. HOT METAL SPACE TEMP (NODE #1)
```
The final part of the graphic data display involves the drawing of four pressure-volume curves for the four working spaces. These curves are drawn only when the flag Q1 = 1 and the time, TIM, is greater than THU. That is, the curves are drawn only when the engine should be moving. The initial engine pressures plot number is calculated on line 320 and the initial volume plot number is calculated on line 340. These are only calculated once. Starting with these values, the next values of these two numbers are calculated on lines 284 and 285. With the initial and next value for both pressure and volume for all four working volumes, four lines (vectors) are drawn (line 286). In lines 287 and 288 the next values become the initial values for the next time around. This part of the program draws four continuous lines tracing out the work diagram for each working space.
C**** DISPLAY GRAPHIC DATA. PART 2
C PLOTTING FOR EVERY TIME STEP OF 4 P-V DIAGRAMS
C CHECK TO SEE IF OPTION I8 ON
IF(Q1-1.)852,853,852
853 IF(TIM-THU)852,852,854
854 DO 985 I=1,4
855 IPV(2,I)=(CVM(8,I)-XLOW)*323/XDV+700
856 JPV(2,I)=PI(I)*190/PDIFF+190*(4-I)
857 CALL VECTOR(IPV(1,I),JPV(1,I),IPV(2,I),JPV(2,I))
858 IPV(1,I)=IPV(2,I)
859 JPV(1,I)=JPV(2,I)
985 CONTINUE
986 CONTINUE

281 IF(TIM-THU)852,852,854
282 DO 985 I=1,4
283 IPV(2,I)=(CVM(8,I)-XLOW)*323/XDV+700
284 JPV(2,I)=PI(I)*190/PDIFF+190*(4-I)
285 CALL VECTOR(IPV(1,I),JPV(1,I),IPV(2,I),JPV(2,I))
286 IPV(1,I)=IPV(2,I)
287 JPV(1,I)=JPV(2,I)
288 CONTINUE
289 CONTINUE

After every five cycles, the screen area where the work diagrams have been
drawn is erased. (See lines 365-372.)

4.2.6 Engine and Vehicle Control Subprogram (EVCS)--Part 1 (Lines 291-455)

Figure 4.4 shows the overall flow chart for CNTLB with more particulars
given to the engine and vehicle control program than was given in Figure 4.2.
The first decision point is to determine whether the cumulative time, TIM, has
reached or exceeded THU, the specified heat up time. If it has not, the
flag IG1 is set at zero. The program jumps directly to increment the time.
The burner and conduction subprogram is executed. This calculates con-
duction and external heat transfer in the air preheater and to the gas
heater of the engine (see Section 4.2.7). After this, the flag IG1 is
tested (Part 2). Since it is less than 1, the program jumps back to the
readout and display and starts through again.

291 C*** ENGINE AND VEHICLE CONTROL SUBPROGRAM PART 1
292 C CHECK TO SEE IF HEAT UP TIME IS EXCEEDED
293 IF(TIM-THU)503,502,502
294 503 IG1=0
295 GOTO 501

Eventually, the air preheater and engine get partially heated up when TIM
exceeds THU. At this point if this is the first time through, the engine gas
inventories are calculated based upon the specified low gas reservoir
pressure, the volumes at zero engine angle and gas temperatures in the
different parts which are assumed to be equal to the metal node temperatures
at that time. Also, the time step is reduced by a factor of 10 to start
out (lines 300-301). However, the time step is finally adjusted in lines
351-357.
Figure 4.4. Overall Flow Chart of CNTLB with Emphasis on Engine and Vehicle Control Subprogram.
Figure 4.4. Part 2.
C FIRST TIME CALCULATION OF GAS MASSES AND INITIALIZE PRESSURES
AND SET GAS TEMPS. TO CURRENT METAL NODE TEMPS.
IF(102-1)504,506,508
502 102=1
C REDUCE TIME STEP AT START OF CRANKING
DDT=DDT/10.
X=PRL*M W/R
DO 507 I=1,4
C NODAL GAS MASSES
W(1,1,I)=X*VHA(1,I)/TM(1,I)
W(1,2,I)=X*VHM+2./(TM(1,I)+TM(2,I))
W(1,3,I)=X*VHD+2./(TM(3,I)+TH(2+I))
W(1,4,I)=X*VRM+2./(TM(4,I)+TM(3,I))
W(1,5,I)=X*VRD/(TM(5,I)+TM(4,I))
W(1,6,I)=X*VRD/(TM(6,I)+TM(5,I))
W(1,7,I)=X*VCD/TWI
W(1,8,I)=X*VCA(1,I)/TWI
C TOTAL GAS MASSES
M(I)=0.
DO 980 K=1,8
M(I)=M(I)+W(I,K,I)
C PRESSURES
P(I)=PRL
C INITIAL PRESSURE PLOT PARAMETERS
JPV(1,I)=(P(I)-PRL)*195/PDIF+195*(4-I)
C AVERAGE GAS AND METAL TEMPERATURES
TBA(1,1,I)=TM(1,I)
DO 981 K=2,6
TMA(K,I)=TM(K-1,I)+TM(K,I))/2.
TMA(7,I)=TWI
TMA(8,I)=TWI
TGA(1,7,I)=TWI
TGA(1,8,I)=TWI
C CUMULATIVE GAS VOLUMES
CVG(1,I)=VHA(1,I)
CVG(2,I)=CVG(1,I)+VHM
CVG(3,I)=CVG(2,I)+VHD
CVG(4,I)=CVG(3,I)+VRM
CVG(5,I)=CVG(4,I)+VRD/2.
CVG(6,I)=CVG(5,I)+VRD/2.
CVG(7,I)=CVG(6,I)+VCD
CVG(8,I)=VT(1,I)
C VOLUME PLOT PARAMETERS
IPV(1,I)=(CVG(8,I)-XLOW)*323/XDV+700
CONTINUE
CONTINUE
If \( T_{DF} \) is between \( THU \) and \( THU + TCR \), the engine is cranked and a torque, \( TST \), is applied to the engine. The net torque accelerating the engine is this torque, when it is applied, plus \( TQS \), the shaft torque realized by the engine pressures and the position of the pistons inside the engine and minus \( TQV \), the retarding torque at the shaft due to the rolling resistance and the air resistance of the vehicle. At first, the only torque causing motion is \( TST \). As gas is added to the engine, \( TQS \) becomes a factor. After the car starts moving, \( TQV \) also becomes a factor.

Based upon the net torque, the engine will move a certain number of degrees. The general formula is:

\[
\text{Net Torque} = \frac{(\text{Effective Moment}) \times (\text{Angular Acceleration})}{\text{Kg m}^2 \text{ radians/sec}^2}
\]

Since a Newton is the force required to accelerate one Kg at the rate of one meter per second per second, the above equation checks dimensionally.

Assume that the engine is idling and the engine itself has a moment of inertia, \( EIN \). Let \( A_1 \), \( A_2 \) and \( A_3 \) be the crankshaft angle in radians for one time step in the past, the current position and one time step in the future, respectively. Thus,

\[
T_{NET} = EIN \frac{\Delta T}{DDT} - \frac{\Delta T}{DDT}
\]

The angular velocity \( \Omega_{MEG} \) is defined at \( \frac{\Delta T}{DDT} \), and the angular increment \( \text{LANG} = A_3 - A_2 \). Making these substitutions, one can obtain:

\[
\text{DANG} = (DDT)^2 \frac{T_{NET}}{EIN} + DDT(\Omega_{MEG})
\]

If the car is in gear, the inertia of the vehicle must be converted to effective inertia as seen by the engine. Equate the kinetic energy of the vehicle to the rotational energy of an equivalent flywheel. Thus:

\[
\frac{1}{2} \text{MIV(SPV1)}^2 = \frac{1}{2} (\text{VIN}) (\Omega_{MEG})^2
\]

So

\[
\text{VIN} = \text{MIV(SPV1)}^2 / (\Omega_{MEG})
\]

The ratio
\[
\frac{\text{SPV1}}{\Omega_{MEG}} = \frac{RGE}{2\pi}
\]
where

SPV1 = vehicle velocity beginning of time step, meters/sec
OMEG = engine angular velocity, rad/sec
RGE = meters traveled/engine revolution

The quantity RGE changes as the gears change and is calculated later (lines 395-419). In the general case the equivalent vehicle inertia must be added to engine inertia EIN.

Therefore, the angle increment is calculated by the formula.

349: C CALCULATE ANGLE INCREMENT
350: 512 DANG=DDT**2*TNET/(EIN+VIN)+DDT*OMEG

Now that DANG is calculated, we must find out whether it is suitable. During the first part when TIM was less than THU, the time step DDT was chosen to give accurate but rapid calculation of the heat up of the engine and air pre-heater. When the engine starts to run, not very accurate calculation of engine performance can be had if DANG is more than 0.5236 radians (30°). Therefore, if DANG becomes greater than this, DDT is halved as many times as it takes to become less than 30°. If engine speed should fall during the driving cycle because of a gear change or a specified speed change, there needs to be a way to increase the time step again by doubling it and if necessary, redoubling it till the angle change is at least 7° (0.12217 radian).

351: C ADJUST TIME STEP SO THAT ANGLE INCR. IS >7 AND <30 DEG.
352: 513 IF(DANG>0.5236)515,515,513
353: 514 DDT=DDT/2.
354: 515 IF(DANG>0.12217)517,517,517
355: 516 DDT=DDT*2.
356: 517 GOTO 512
357: 518

Next, the engine angle in both degrees and radians is indexed. If the angle is greater than 360 degrees, the computer won't handle it as accurately so the program should keep it within this range.

358: C INDEX ENGINE ANGLE MEASURES
359: 516 EARAD=DANG+EARAD
360: 517 EADEG=EARAD/RAD
361: 518 REV=REV+DANG/(2.*PI)
362: 519 IF(EADEG-360.)239,240,240
363: 240 EADEG=EADEG-360.
364: 241 EARAD=EARAD-2.*PI

Since this part of the program is entered once per engine revolution, it is a good place to put the erase program. If the graphic option is on (Q1 = 1), the program counts the number of revolutions with the revolution counter, NER. When it reaches 5, it resets the counter and calls ERASE.
365: C ERASE PV PLOT FIELD AFTER EVERY 5 REVOLUTIONS
366: IF(Q1-1.) & 239; 151, 239
367: 151 IF(NER-5) & 152; 150, 150
368: 150 NER=0
369: CALL ERASE
370: GOTO 239
371: 152 NER=NER+1
372: 239 CONTINUE

The subroutine ERASE will now be explained. This subroutine (lines 887-921) using the conventions for the Retrographics package and presumably for the Tektronics Plot 10 software draws a series of black lines. Each line goes from 2 to 777 in the vertical direction (see Figure 4.3). Each time ERASE is called, a series of black lines are drawn from the horizontal position 710 to 1013. Although the number of plotable points in the horizontal direction is 512 and the addresses are 1023, it would seem that every other address would do a complete erase. It did not. By this means all the pressure-volume diagrams are erased so that one can see where the new ones fall. (See Appendix C for additional explanation of this subroutine.)

987: C SUBROUTINE USED TO ERASE PV DISPLAY FIELD
988: SUBROUTINE ERASE
991: DO 30 JP=710, 1013
992: CALL CONOUT(GS)
993: CALL CONOUT(ES)
994: CALL CONOUT(DE)
995: YH=777/32+32
996: YL=MOD(777, 32)+96
997: XH=JP/32+32
998: XL=MOD(JP, 32)+64
999: CALL CONOUT(YH)
1000: CALL CONOUT(YL)
1001: CALL CONOUT(XH)
1002: CALL CONOUT(XL)
1003: DO 10 I=1, 200
1004: M=M+1
1005: 10 CONTINUE
1006: YH=2/32+32
1007: YL=MOD(2, 32)+96
1008: CALL CONOUT(YH)
1009: CALL CONOUT(YL)
1010: CALL CONOUT(XH)
1011: CALL CONOUT(XL)
1012: DO 20 I=1, 200
1013: M=M+1
1014: 20 CONTINUE
1015: CALL CONOUT(ES)
1016: CALL CONOUT(AA)
1017: CALL CONOUT(US)
1018: CALL CONOUT(CA)
1019: 30 CONTINUE
1020: RETURN
1021: END
Now that a proper time step has been chosen, the next thing is to determine what should be done with the engine pressure. When the engine is idling, the engine pressure is adjusted to keep the engine speed adjusted to maintain a specified vehicle speed schedule. Therefore, TIM is compared against TI2, the cumulative time in which the engine is put in gear to determine which method is used to adjust pressure and to compute vehicle inertia and vehicle friction (see Figure 4.4).

373: C CHECK TO SEE IF ENGINE SHOULD BE IDLEING OR IN GEAR
374: IF(TIM-TI2)519.519.520

If the engine is idling, IG1 is set to 1. If it is in gear, IG1 is set to 2. So far it makes no difference subsequently whether IG1 is 1 or 2. Possibly later modifications may utilize this.

For the base case driving cycle, the idling comes before the driving. The current engine speed, OMEG, is compared with the specified idling engine speed OM1. The valve setting for the addition or removal of gas is diagrammed in Figure 4.5. Three valves are used in series (see Figure 4.6).

Valve 1. A slide valve which is open between +45° from bottom dead center of each piston in the four cylinder array. The opening of these four slide valves relate to the engine angle as follows:

### Table 4.1

<table>
<thead>
<tr>
<th>Engine Angle (degrees)</th>
<th>Number of Cylinder with Slide Valve Open</th>
<th>Number of Working Space Having Pressure Adjusted</th>
</tr>
</thead>
<tbody>
<tr>
<td>315 to 45</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>45 to 135</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>135 to 225</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>225 to 315</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

Valve 2. A throttle valve which is closed when the engine speed is exactly the desired speed. At a speed difference, PBIS, on either side of the speed goal, the throttle valve becomes full open at MIR.

Valve 3. A switch valve. The throttle valve is connected to the high pressure reservoir. When the engine speed is below the desired speed and to the low pressure reservoir when the engine speed is above the desired speed.

The author feels that this control scheme is reasonably realistic and similar to control schemes actually used. Other control methods can be substituted.

25
Figure 4.5. Engine Speed Control Scheme.

Figure 4.6. Engine Control Valves.
The above programming sets up the subroutine to calculate which compartment is to have its gas inventory adjusted and by how much. Since this is the first time the subroutine is used, it will be explained here.

For each time step one of the four compartments has gas added to or removed from it. The gas is added at inlet cooling water temperature to the adiabatic cold space. It is removed at the same place it is added. The working space that has received the gas change is noted by setting flag IG3 to 1, 2, 3 or 4. In the previous programming X is set at the high reservoir pressure, PRH (line 388) or the low reservoir pressure, PRL (line 382). The pressure in the working space that is having its pressure adjusted, PX, approaches pressure X exponentially with a time constant MIR1. MIR1 is set by the error in engine speed, OMEG, compared to what is desired (see Figure 4.5). Subroutine MASS is also called from line 440 where the control is from vehicle speed rather than engine speed.

Originally, at this point the mass of gas in the working space was adjusted, thus the name. By experience, it was found that the pressure must be adjusted instead to maintain numerical stability.
The final thing that needs to be done in this branch of the program where the engine is not in gear is to find the new engine speed. This computation was delayed till this point so the old engine speed can be used to adjust engine pressure.

```
390: C COMPUTE NEW ANGULAR VELOCITY
391: OMEG=DANG/DDT
392: GOTO 501
```

For the case where the engine is in gear, a more complicated set of determinations are required. This also is diagrammed in Figure 4.5 (lines 393-449). The first thing is to set the gear ratio (lines 395-420). The equivalent of a clutch is modeled by having the gear ratio change from 0 to the first gear ratio RGE1 in the specified gear change time GCT. The programming specifies a linear change in this ratio. Figure 4.7 shows how the other gear ratios for the second or third gear are applied depending on the vehicle speed. A linear change over the same gear change time is programmed in.

![Diagram of Gear Ratio Control](image)
Once the gear ratio is determined, the effective vehicle inertia, \( V_{\text{IN}} \), is determined. This equation was derived in Section 4.2.6.

\[ V_{\text{IN}} = \text{MI} \times \frac{\text{PG} \times (2 \times \text{PI})}{1 \times 2} + 2 \]

Next, the scheduled vehicle speed needs to be determined to decide which way the control will go. Resident in the program is a ramp change in speed from zero to the cruising speed followed by a steady cruising speed until the end of the driving cycle.

The adjustment of engine pressure to control vehicle speed is standard in automotive Stirling engines. Other things like dead volume control or piston stroke control can be added as options at this point. The control scheme is parallel with that used to control engine speed during idle. (See Figure 4.5.) If the vehicle speed, \( V_{\text{SPV1}} \) is within the proportional band of \( \text{PBVS} \) of the scheduled vehicle speed, \( V_{\text{SPVD}} \), then the valve setting \( \text{MIR1} \) is proportional to this error. If the error is beyond this band in either direction, the valve setting is \( \text{MIR} \).
Once the valve setting is determined, the switch valve to connect the engine space to either the high pressure reservoir or the low pressure reservoir is set by making X either PRL if gas should come out of the engine or PRH if gas should go into the engine. Once this is determined the subroutine mass is called because two different parts of the program uses it. Subroutine determines which engine compartment gets or gives the gas. It identifies this working space for later use (sets IG3) and determines the new pressure, PX. The subroutine has already been explained in this section.

428:  C ADJUST ENGINE PRESSURE TO CONTROL VEHICLE SPEED
429:  943 IF(SPVI-SPVD)930,940,940
430:  940 IF(SPVI-(SPVD+PBVS))941,941,942
431:  942 MIR1=MIR
432:  GOTO 943
433:  941 MIR1=MIR*(SPV1-SPVD)/PBVS
434:  943 X=PRL
435:  GOTO 955
436:  930 IF(SPVI-(SPVD-PBVS))931,931,932
437:  931 MIR1=MIR
438:  GOTO 933
439:  932 MIR1=MIR*(SPVD-SPV1)/PBVS
440:  933 X=PRH
441:  955 CALL MASS(IG3, PX, MIR1, DDT, X, P1, EADEG)

Next, the rolling friction and air friction are determined. The rolling friction, RF, is in Newtons of retarding force applied to the vehicle. The formula used is from Reference 1. The air friction formula is from the same source. The original rolling resistance formula is:

\[ R = \left( \frac{W}{65} \right) + (1.4 \times 10^{-3} V) + (1.2 \times 10^{-5} V^2) \]

where \( V \) is vehicle velocity in feet per second and \( W \) is vehicle weight in pounds. \( R \) is the rolling friction in pounds force.

Units and nomenclature have been converted to:

- \( RF \) = rolling friction, Newtons
- \( MIV \) = inertial mass of vehicle, Kg
- \( SPV1 \) = vehicle speed, meters/second

The air drag specified is for a combined drag coefficient times frontal area of 12 ft² = 1.12 m² = AFR. The air friction is determined by the formula:

\[ AF = \frac{\rho(AFR)}{2} (SPV1)^2 \]

where

- \( AF \) = air friction, Newtons
- \( \rho \) = air density at 300 K
  \[ = \frac{29 \text{ g/mol}}{22.414 \text{ g/mol}} \times \frac{273}{300} \times \frac{1000 \text{ L/mol}}{1000 \text{ g/kg}} = 1.1774 \text{ Kg/m}^3 \]
- \( AFR \) = frontal area times flow coefficient, m²
- \( SPV1 \) = vehicle speed, m/sec
Thus, 

\[ AF = \frac{1.1774}{2} (AFR) (SPV1)^2 \]

In CNTLA,

\[ KAR = 0.589 (AFR) \]

The retarding torque that the rolling and air frictions of the vehicle apply to the engine also depends upon the gear ratio RGE.

442: C TORQUE DUE TO VEHICLE ROLLING FRICTION, AIR FRICTION
443: \( RF = MIV * (0.151 + 0.000693 * SPV1 + 0.000195 * SPV1^2) \)
444: \( AF = KAR * SPV1^2 \)
445: \( T0V = (RF + AF) * RGE / (2 + PI) \)

Finally, after all the uses for the old engine speed (angular velocity) and the old vehicle speed have been applied, new values for both of these are calculated in this part of the program. The engine speed, \( \Omega_E \), is calculated the same whether it is in the idling or in the in-gear part of the program. However, they cannot be combined because in this part the new vehicle speed, \( SPV1 \), depends upon \( \Omega_E \) and also upon \( RGE \), the working gear ratio, which is only defined in this part of the program.

446: C COMPUTE NEW ANGULAR VELOCITY
447: \( \Omega_E = DANG / DDT \)
448: C COMPUTE NEW VEHICLE SPEED
449: \( SPV1 = \Omega_E * RGE / (2 + PI) \)

Now the two parts of the program come together. At this point a check display to the screen is included so that the operator may monitor the solution more accurately than the graphical display does. (See Section 6 for additional details.)

450: C ONE LINE CHECK DISPLAY TO SCREEN
451: 501 WRITE(5,9030)TIM, CF, REV, OMEG, SPV1, SPV2D, RGE, NGC
452: 9030 FORMAT(7EQ1.1D)

Whether the engine is stopped, idling or in gear (see Figure 4.4), the cumulative time counter, \( TIM \), is incremented.

453: C INDEX TIME
454: \( TIM = TIM + DDT \)
455: C*****END ENGINE AND VEHICLE CONTROL SUBPROGRAM PART 1

This is the end of the explanation of the engine and vehicle control subprogram--part 1. Explanation of the other two parts will be given as they appear in the program.

4.2.7 Burner and Conduction Subprogram

This subprogram along with part of the control program is the only one operative when the engine is stopped. It takes care of controlling the average temperature of the heater tubes at the target temperature and figures heat conduction through the engine to the cooling water. It also computes the transient response of the air preheater.
This subprogram will be explained in the order of calculation. However, before very much in this subprogram will make sense, the nomenclature must be explained.

4.2.7.1 Nodal Organization

Figure 4.8 shows a schematic of the burner and air preheater. Eight metal nodes are chosen since this gives rapid computation and reasonable accuracy (see Appendix A). The metal node temperatures in the air preheater EX(1) to EX(8) must be initialized to ambient or whatever the input file says. (See Section 4.2.2.)

![Figure 4.8. Burner and Air Preheater Schematic.](image)

Figure 4.8 shows the metal node nomenclature for the engine needed for burner heating, heat conduction, and engine operation. There are 8 metal nodes defined. Each node has the following properties:

1. a temperature, TM(X, Y), K,
2. a location, WM(X, Y) in cm$^3$ of gas volume from the hot end of the engine to the node point,
3. a thermal conductivity, KM(X), from the node point to the next lower one, w/cm K,
4. a heat capacity, CM(X), of the material surrounding the node point to half way to the next node point, W/K.

In the above list the arguments of the four arrays defined were listed as...
Figure 4.9. Metal and Gas Node Nomenclature.
X and Y. In this case X is the number of metal nodes, 8, and Y is the number of working spaces in the engine, 4.

The gas volume nomenclature for the engine is also shown on Figure 4.9. VHA(X,Y) is the variable hot volume which is assumed to be adiabatic. This is a very good assumption except for a small portion of each cycle. X is for the beginning and end of the time step and Y is for the four cylinders of the engine.

Similarly, VCA(X,Y) is the variable cold volume assumed to be adiabatic.

The constant dead volumes are also identified in Figure 4.9. The gas in these volumes is assumed to attain metal temperature once each cycle. In the engine torque and internal heat transfer subprogram, the heat transferred at each metal node is computed for this equilibration. Afterward the temperatures of the metal nodes are adjusted because of this heat transfer. For well designed engines, the assumption of isothermal spaces in all except for the variable volume spaces is fairly good. The assumption was made to speed up the calculation.

The thermal conductivity attached to metal nodes 1 to 6 is the watts of heat that would pass per °K of temperature difference. It pertains to the path toward the next lower node number. Note that these thermal conductivities are the same for all cylinders.

The heat capacity attached to metal nodes 1 to 5 determines how fast the temperature of each node changes due to thermal imbalance. All metal node temperatures are adjusted each time step due to external convection and metal conduction.

4.2.7.2 Heater Temperature Control

Now we will proceed with the explanation of the program.

The first thing is the indexing of the metal node temperatures in the air preheater. In the unified printout (see Section 4.2.4), the temperatures of the air (TIN(I)) and the flue gas (TOU(I)) (see Figure 4.8) relate to the original air preheater metal node temperatures, EX(I), rather than the metal node temperatures at the end of the time step EY(I) after heat transfer has taken place. Therefore, this indexing is done at the start of the subprogram.

```
456  C        BURNER AND HEAT CONDUCTION SUBPROGRAM
457  C  INDEX ASH METAL NODE TEMPERATURES
458     DO 8050 I=1,N
459     8050  EX(I)=EY(I)
```

Next, the average temperature for the gas heater metal at the start of the time step is found. According to Figure 4.9 the gas heater has a node on each end of each of the heaters. These temperatures may be different due to different conduction effects or the effect of the gas flowing inside the engine. An average is taken of the temperature of all 8 metal nodes (2 for each working space).
Then the temperature error is determined and the current fuel flow is determined from it by a proportional control algorithm. Figure 4.10 shows this response scheme. It is a simple proportional band control scheme. The average temperature will always droop a bit below the goal. Better control schemes can be substituted if needed. The fuel usage from the start is accumulated. The cumulative fuel usage, Fuel, is initialized on line 675 of CNTLA. Therefore, the value for the cumulative fuel usage is shown at the end of the program.

Figure 4.10. Control Scheme for Engine Heaters.
4.2.7.3 Heat Transfer Factor Calculation

This next part of the subprogram has to do with calculating heat transfer factors to use in computing heat transfer in the air preheater and to the engine heater tubes. Since this process is complicated and since the results involve correlations that are only good to ±20%, it was decided to go through it once at the beginning and then go through it again when the fuel flow has changed more than 20% in either direction. The following shows the if statements that direct the calculation around this part if CFL < CFF < CFH.

475: C CHANGE HEAT TRANSFER FACTORS IF CFF HAS CHANGED SIGNIFICANTLY
476: IF(CFF-CFL)404.420.420
477: 404: IF(CFF-CFH)420.420.420

This next part gives the basis for calculating the heat transfer factors for both sides of the air preheater and the gas heater. First, the air flow and the heat capacities must be determined. With the fuel flow specified, the air flow is specified in order to give 10% excess air. The air fuel ratio was based upon normal octane as an average for the fuel actually used. The combustion equation is:

\[
C_8H_{18} + 12.5 O_2 + 1.25 O_2 + 51.73 N_2 \rightarrow 8 CO_2 + 9 H_2O + 1.25 O_2 + 51.73 N_2
\]

10% excess

On a one gram mole basis the fuel burned weighs 114.14 g and the air used to burn it weighs 1889.47 g. Therefore, for these assumptions the ratio of air to fuel, RAF = 16.55 as given in the base case. Using this same chemical equation the heat capacity of the flue gas was averaged as follows:

- CO_2 \quad 8 \times 11.94 = 95.52
- H_2O \quad 9 \times 9.928 = 89.52
- O_2 \quad 1.25 \times 7.94 = 9.93
- N_2 \quad 51.73 \times 7.50 = 386.98

\[0.63 \text{ g mol} \quad 576.22\]

Average flue gas heat capacity = \[\frac{576.22}{576.22} = 8.23 \text{ cal/g mol C}\]
The molecular weight of the flue gas is 26.63. Therefore, the heat capacity of the flue gas, \( CP_{FG} \), in the units used in this calculation is 1.20 \( \frac{J}{g \cdot K} \). The heat capacity for air, \( CP_{A} \), is 1.03 \( \frac{J}{g \cdot K} \). These values are given in the program and can only be changed by revising the data statement (see CNTLB line 32).

Given the fuel flow, the air flow is determined. From the air flow, the mass velocity, \( G_{APH} \), of air in terms of grams per second of air flowing per cm\(^2\) of flow area is computed. Next the Reynolds number is defined. That is,

\[
RE = \frac{DEQ \cdot G_{APH}}{\text{viscosity of air}}
\]

The equivalent diameter, \( DEQ \), of the rectangular flow area is calculated as 4 times the flow area divided by the wetted perimeter. (See line 669 of CNTLA.) The viscosity of air at 700 K is about \( 4 \times 10^{-4} \) g mass/cm sec. The reciprocal of this, 2500, is used to compute the Reynolds number, \( RE \).

From the Reynolds number, the heat transfer coefficient is calculated by means of the correlation shown in Figure 4.11. This correlation is used for both the air and the flue gas side of the air preheater. It is subroutine STANTN.

![Figure 4.11. Heat Transfer Correlation Used for the Air Preheater (2).](image-url)
The output of this correlation is taken as the Stanton number times the Prandtl number to the two-thirds power, the wall temperature factor is ignored. Thus,

\[ \text{STN} = \frac{h}{\left( \frac{\text{GapH}}{(\text{CF})} \right) \left( \text{Pr}^{2/3} \right)} \]

At 700 K, the specific heat at constant pressure for air, CF is 1.052 and the Prandtl number of 0.864. Thus, the heat transfer coefficient is:

\[ h = (\text{STN}) (\text{GapH}) (1.19) \]

In modeling the air preheater a number of different mathematical models were tried. It was desired to have something simple but still take into account the transient heat up of the air preheater starting at the hot end. The scheme that was chosen is shown in Figure 4.12. It is assumed that the air preheater is divided into N segments. For the main program N was chosen as 8. In Appendix A the effect of N on the accuracy of calculation is discussed.

![Figure 4.12. Air Preheater Calculation Scheme.](image-url)
In each segment the air and flue gas are separated by a plate with a constant temperature for that segment. It would be more realistic to assume a constant temperature gradient but the mathematical formulation was too complicated and would involve an iterative solution at each time step. The method chosen will be sufficiently accurate except at very low flows. Note that for each node both the air and the flue gas temperature approach the temperature of the air preheater plate. Both of these processes involve heat transfer to or from the plate. Then there is the process of conduction from one metal node to the next. In CNTLB the temperature of each metal node, EX(N), is changed after both air and flue gas heat transfers are calculated. In WARM (Appendix A) metal temperatures were changed twice and heat conduction along the metal was ignored.

The calculation starts by setting the metal node temperatures, EX(1) to EX(8). The inlet air temperature, TIN(1) is taken as the ambient air temperature. TIN(2) is calculated from TIN(1) as will be shown hereafter. TIN(3) is calculated from TIN(2) and so on up the stairs to TIN(9), the temperature of the air leaving the air preheater. This preheated air burns with the fuel to produce a gas with a temperature FLAME. It exchanges heat with four sets of engine heaters which may have different temperatures due to the internal workings of each part of the engine. Each engine section has a metal node at both ends of the engine heater. It is assumed that the same heat transfer coefficient applies to all heater nodes. The flue gas leaving the engine heaters has cooled and may be at different temperatures. It is averaged to become TOU(9). The flue gas is now cooled down along the stairstep air preheater in the same way the air heats up. Finally, the temperatures of the air preheater metal is adjusted due to air and flue gas heat transfer and metal conduction. Also, the temperatures in the engine are adjusted due to metal conduction. In another part of the program which is active when the engine rotates the engine metal node temperature will be further adjusted due to heat transfer with the working gas. In all these calculations the time step must be small enough so that the metal node temperatures do not change very much each increment. If they did, calculational instabilities would build up and destroy the simulation.

For the first increment in the heat exchanger, the heat transferred from the metal to the air, H, can be expressed two different ways.

\[
H = CPA \times \frac{CFF \times RA \times (TIN(2) - TIN(1))}{\text{Heat Transfer Capacity Air Flow Temperature Rise}}
\]

Heat watts \quad \text{Heat Air Flow Temperature Rise} \quad 3/g K \quad g/sec \quad K

and

39
\[
H = h - A_h \cdot \frac{(EX(1) - TIN(1)) - (EX(1) - TIN(2))}{\ln \left\{ \frac{EX(1) - TIN(1)}{EX(1) - TIN(2)} \right\}}
\]

where
\[ h = STN \cdot GAPH \cdot 1.19 \]
\[ A_h = LAPH \cdot WAPH \cdot NAPH \cdot \frac{2}{NO} \]

When the above two equations are combined and solved for TIN(2), the result is:

\[
TIN(2) = EX(1) - \frac{EX(1) - TIN(1)}{\exp(X)}
\]

where
\[ X = UXX \cdot STN \cdot GAPH \cdot 1.19 / CFF \]
\[ UXX = \frac{LAPH \cdot WAPH \cdot 2 \cdot NAPH}{NO \cdot RAF \cdot CPA} \]

In evaluating Equation 1, it is easily possible for X to be large enough to overflow the number size limit of a computer. For the Altos Z 80 based microcomputer used to develop this program, \( \exp(32) \) was about as large as the computer would go without giving an overflow error. Therefore, if \( X > 32 \), it is made equal to 32. Therefore, the heat transfer factor is:

\[ XY = \exp(X) \]

and the final equation to find the air temperatures in succession is:

\[
TIN(2) = EX(1) - \frac{(EX(1) - TIN(1))}{XY}
\]

Similarly, TIN(3) is calculated from TIN(2) and so on to TIN(9).

All of the above is necessary to explain the programming lines below, to find the heat transfer factor for the air side of the air preheater. The constant UXX is evaluated on line 673 in CNTLA and brought over through the data file.

482: \( X=UXX*STN*GAPH+1.19/CFF \)
483: IF \( X \ GT \ 32 \) \( XY=32. \)
484: \( XY=\exp(X) \)

The heat transfer factor for the flue gas side of the air preheater is calculated in the same way as the air side. The flow rate is greater and the heat capacity is greater. A quantity UXY analogous to UXX is brought over from CNTLA and used here.

485: C HEAT TRANSFER FACTOR, FLUE GAS SIDE
486: GAPH=CFF*(PA1)/AFAPH
487: RE=DE0+GAPH+2500.
488: CALL STRNTN(RE, STN)
489: X=STN*GAPH+1.19+UXY/CFF
490: IF \( X \ GT \ 32 \) \( X=32. \)
491: \( XZ=\exp(X) \)

40
Next, the heat transfer factor, \( X_H \), for the flame heating the heater tubes must be calculated.

Direct flame heated Stirling engines always have the outside heat transfer coefficient controlling.

The equation and the values assumed to be valid for this case were taken from Table 4.2.

### Table 4.2

**EQUATION PARAMETERS USED FOR HEAT TRANSFER TO GAS HEATER (3)**

<table>
<thead>
<tr>
<th>( x_L = g_L / D_0 )</th>
<th>( x_T = 1.25 )</th>
<th>( x_T = 1.5 )</th>
<th>( x_T = 2 )</th>
<th>( x_T = 3 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( b_2 )</td>
<td>( n )</td>
<td>( b_2 )</td>
<td>( n )</td>
<td>( b_2 )</td>
</tr>
<tr>
<td>Staggered:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.600</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.900</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.000</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.125</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.250</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.500</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.000</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.000</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>In line:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.250</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.500</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>2.000</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.000</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In the 4L23 engine there is one row of heater tubes. In the P-40 engine there are two rows widely separated. Assume that the pitch to diameter ratio is 1.25. That is, each tube is separated from the next by a space \( \frac{1}{4} \) the outside diameter of the tube. Assume that the transverse pitch is large, say, 3 times the outside diameter. Also, assume that the heated length includes the front and back row and negligible for the bend. Thus, the gas heater minimum flow area is:

\[
AMF = \frac{DOH}{4} \times \frac{LHH}{2} \times NTH \times 4 \times \text{cylinders per engine}
\]

\[
= DOH \times LHH \times NTH / 2
\]

Therefore, the maximum mass velocity is:

\[
G_{MAX} = CF \times (RA_1) / AMF
\]
At 1000 K the viscosity of air is:
\[ \mu_f \approx 6 \times 10^{-4} \text{ g/cm sec} \]
and the thermal conductivity is:
\[ k_f \approx 7 \times 10^{-4} \text{ w/cm K} \]

Therefore, by substituting into the equation from Table 4.2 and simplifying, the heat transfer coefficient is found to be:

\[ U_H = \frac{DOH \times CFF \times RA1}{AMF \times 0.0006} \times 0.592 \times 0.00022/DOH \]

It is also not necessary to evaluate the heat transfer coefficient every time step since it changes little so it is grouped with the evaluation of the heat transfer coefficient for the air side and is only re-evaluated when the flow changes appreciably.

Each part of the engine may have a different heater temperature depending upon what is going on inside. However, it is assumed that \( \frac{1}{4} \) of the flame passes through each of the four engine sections. For each section the heat transfer can be expressed two ways (see Figure 4.13):

By temperature change:
\[ H = \frac{CFF}{4} \times RA1 \times CFFG \times (FLAME - T3A(Y)) \]

And by heat transfer:

Let
\[ X = \frac{TM(2,Y) + TM(3,Y)}{2} \]

\[ H = U_H \times AH \times \frac{(FLAME - X) - (T3A(Y) - X)}{\ln\left(\frac{FLAME - X}{T3A(Y) - X}\right)} \]

Combining the above two equations gives:
\[ T3A(Y) = X + (FLAME - X)/XH \]

where
\[ XH = \exp\left(\frac{U_H \times AH \times 4}{CFF \times CZ}\right) \]
\[ AH = PI \times DOH \times LHH \times NTH \]
\[ CZ = CFFG \times RA1 \]

If the argument of the exponential is greater than 32 it is made 32 to prevent overflow in the computer.
All the above explanation is necessary to show how the heat transfer factor, $X_H$, is computed and used. The programming is:

487  C HEAT TRANSFER FACTOR: GAS HEATER
488  UH=DOH+CFH*PAL/AMF+0.006*++0.592+0.00022/DOH
489  VH=+UH+AH+CFE+CFH
490  TCHEAT=ST Tempo
491  VH=EXP(VH)

Every time the heat transfer factors are calculated the flow bounds must be recalculated.

492  C RESET FLOW BOUNDS
493  CFH=1 2*CFE
494  CFL=0 8*CFE

4.2.7.4 Air Side Temperature Calculation

Now that the heat transfer factors are calculated (if they have had to be), the temperatures through the air and flue gas circuit can be quickly determined. In this calculation it is assumed that the thermal lag due to the heat capacity of the metal parts is so important that the added complication of figuring transit times for the gas around the circuit is not necessary. Therefore, steady state temperatures are calculated for the gas side. Calculation starts with ambient air at the inlet to the air preheater and works...
around the circuit. First, the air temperatures in the preheater are calculated sequentially as has already been explained.

```
500  C CALCULATE APH AIR TEMPERATURES
501    DO 427 I=1,N
502    TIN(I+1)=EX(I)-(EX(I)-TIN(I))/XY
```

2. Burner Calculation

Next, the preheated air enters the burner. The temperature rise is given by the equation

\[ \text{LHV} \times 1000 \times \text{CFF} = \text{CFF} \times (\text{RAF} + 1) \times \text{CPFG} \times \text{DT2} \]

heat supplied by fuel combustion, watts
heat absorbed by flue gas temperature rise, watts

which reduces to:

\[ \text{DT2} = \frac{\text{LHV} \times 1000}{(\text{CPFG}) \times (\text{RAF} + 1)} \]

LHV = lower heating value of fuel = 46.432 KJ/g = 20,000 BTU/lb
CPFG = heat capacity of flue gas = 1.20 J/g K
RAF = ratio of air flow to fuel flow, J/g
(\text{RAF} + 1) = ratio of flue gas flow to fuel flow
CFF = current fuel flow, g/sec
DT2 = temperature rise in flue gas temperature (neglecting disassociation)

Note that DT2, in the simple way it is calculated here, neglecting dissociation and heat loss through burner insulation, is not dependent on flue flow. DT2 comes from CNTLA, line 671.

```
503  C FIND FLAME TEMPERATURE
504    FLAME=TIN(N+1)+DT2
```

4.2.7.6 Heat Transfer to Gas Heaters

Next, the four effluents from the heaters are calculated as has been explained.

```
505  C DETERMINE OUTLET FLUE GAS TEMP. FROM HEATERS
506    DO 437 I=1,4
507    X=(TM(2,I)+TM(3,I))/2
508    T3A(I)=X+(FLAME-X)/XH
```

The flue gas temperatures are averaged and the one outlet temperature, TOU(N+1), is obtained.

```
509  C AVERAGE FLUE GAS TEMPERATURES
510    TOU(N+1)=(T3A(1)+T3A(2)+T3A(3)+T3A(4))/4
```
4.2.7 Flue Gas Side Temperature Calculation

Finally, the flue gas temperatures down the stairsteps of the air preheater are calculated as has been explained.

4.2.7.8 Metal Temperature Adjustment in Air Preheater

Next, the metal node temperatures in the air preheater must be adjusted for heat transfer and conduction. For the first node the heat lost, in joules, to the air is:

\[ X = CFF \times RA1 \times CPA \times (TIN(2) - TIN(1)) \times DT \]

The heat gained from the flue gas is:

\[ Y = CFF \times RA1 \times CPFG \times (TOU(2) - TOU(1)) \times DT \]

The heat gained by metallic conduction is:

\[ ZZ = KM \times (TMAPH \times NAPH \times NAPH \times 2) \times \frac{(EX(2) - EX(1))}{(LAPH/NO)} \times DT \]

\[ ZZ = KAPH \times (EX(2) - EX(1)) \times DT \]

The heat capacity of most metals on a volume basis is about the same, 500 J/cm³K. Thus, the heat capacity in each metal node is:

\[ CMAPH = \frac{LAPH \times WAPH \times 2 \times NAPH \times TMAPH \times 5.00}{NO} \]

Therefore, a heat balance on the first metal node is:

\[ CMAPH(EY(1) - EX(1)) = ZZ + Y - X \]

Therefore, the metal node temperature at the end of the time step is:

\[ EY(1) = EX(1) + (ZZ + Y - X)/CMAPH \]

This derivation is different for the middle nodes and the other end nodes but the concept is the same. It is assumed that the air preheater metal is not connected to any other heat source or heat sink except the gases flowing through it. Based upon the above explanation the following programming calculates the new air preheater metal node temperatures.
515: C CHANGE APH METAL NODE TEMP DUE TO CONVECTION AND CONDUCTION
516: DO 430 I=1,N
517: X=CFF*RA1*CPA*(TIN(I+1)-TIN(I))*DDT
518: Y=CFF*RA1*CPFG*(TOU(I+1)-TOU(I))*DDT
519: IF(I-1)448,448,450
520: 450 IF(I-8)449,451,451
521: 448 ZZ=KAPH*(EX(I+1)-EX(I))*DDT
522: GOTO 452
523: 449 ZZ=KAPH*(EX(I+1)-2.*EX(I)+EX(I-1))*DDT
524: GOTO 452
525: 451 ZZ=-KAPH*(EX(I)-EX(I-1))*DDT
526: 452 CONTINUE
527: 430 EY(I)=EX(I)+ZZ+Y-XX/CMAPH

4.2.7.9 Metal Temperature Adjustment in the Engine

Five metal nodes in each of the four parts of the engine float in temperature. They receive and give up heat by conduction and by being heated by the heater all the time. This part will now be explained.

Each node as shown in Figure 4.9 is a special case but the formulation for calculating the same node in the four parts of the engine is the same. The calculation for each engine metal node will now be explained.

Metal Node 1 is the metal around the hot space, half the way to the water cooled portion of the engine cylinder. The thermal conductance to the cooling jacket is:

\[ KME(1) = \frac{KM * PI * DCY * (TCY + THC)}{HCL} \]

KME(1) to KME(6) are brought over from CNTLA.

The thermal conductance from the heater is:

\[ KMB(2) = \frac{KM * PI * DIHM * WTM * NTHM}{LHM} \]

The heat capacity of metal node 1 also involves the same specific heat capacity of 5.00 j/cm^2K. This heat capacity in j/K degree change is computed as follows:

The metal volume of the end caps is:

\[ X = PI^4 * DCY^2 * (THH + TGH) \]

The metal volume of the cylinder wall belonging to the node is:

\[ Y = PI * DCY * (TCY + THC) * HCL/2 \]

The metal volume of the heater manifold belonging to the node is:
ZZ = PI * D1HM * WTHM * NTHM * LHM/2

Thus the nodal heat capacity is:

\[ CM(1) = (X + Y + ZZ) \times 5.00 \]

CM(1) to CM(5) is brought over from CNTLA.

In the calculation the metal node temperatures will be changed once due to flame heating and metal conduction and then later in the program due to internal heat transfer. One must have two sets of metal node temperatures. Each temperature figures in several equations. It would not do to mix new and old temperatures in the calculations. In metal node 1, for the time step DDT, the heat lost to the cooling jacket is:

\[ A = KME(1) \times (TM(1,I) - TWI) \times DDT \]

The heat gained through the heater manifold is:

\[ B = KME(2) \times (TM(2,I) - TM(1,I) \times DDT \]

Thus, a heat balance of metal node 1 gives:

\[ CM(1) \times (TM(1,I) - TM(1,I) = B - A \]

Therefore, the new metal temperature due to one time step's worth of conduction is:

\[ TM(1,I) = TM(1,I) + \frac{B - A}{CM(1)} \]

Note that the 1 represents the four cylinders which will have different internal heat transfers.

<table>
<thead>
<tr>
<th>CM</th>
<th>CHANGE ENGINE METAL NODE TEMPS DUE TO COND AND OUTSIDE CONV</th>
</tr>
</thead>
<tbody>
<tr>
<td>GCM</td>
<td>D1HM * LHM * LTHM * LTHM --------------------------------</td>
</tr>
<tr>
<td>GTHM</td>
<td>G + ME1 = TM(1,I) + TM(1,I) + TM(1,I) -------------------</td>
</tr>
<tr>
<td>TG1</td>
<td>F1 + ME1 = TM(1,I) + TM(1,I) + TM(1,I) + DDT</td>
</tr>
<tr>
<td>TG2</td>
<td>F1 + ME1 = TM(1,I) + TM(1,I) + TM(1,I) + DDT</td>
</tr>
</tbody>
</table>

Metal node 2 is centered at the junction between the heater manifold and the heater. It includes half the heater manifold and half the heater. Pertaining to it are thermal conductance KME(3), already defined, and KME(3) between the two ends of the heater. Thus:

\[ KME(3) = K + PI4 \times (D1H ** \_2 - D1H ** _1) \times NTH/LHH \]

The heat capacity of metal node 2 involves the other half of the heater manifold metal volume, already calculated as Z, and half of the heater metal volume which is:

\[ X = PI4 \times (D1H ** \_2 - D1H ** _1) \times NTH \times LHH/2 \]

Thus, the nodal heat capacity is:

\[ CM(2) = (C - X) \times 5.00 \]
In metal node 2 the heat loss in joules for the time step DDT to node is already calculated as B. The heat loss to metal node 3 by conduction is:

\[ A = \text{KME}(3) \times (\text{TM}(2, I) - \text{TM}(3, I)) \times \text{DDT} \]

The heat gain due to flame heating is:

\[ C = \frac{\text{OFF} \times \text{RA1} \times \text{CPFG} \times (\text{FLAME} - \text{T3A}(I))}{4} \times \text{DDT/2} \]

since half of the heat from the flame is assumed to go to node 2 and half to node 3. Therefore, by a heat balance

\[ \text{CM}(2) \times (\text{TM1}(2, I) - \text{TM}(2, I)) = C - A - B \]

Thus, the new temperature on metal node 2 after one time step's worth of conduction and external heat transfer is:

\[ \text{TM1}(w, I) = \text{TM}(2, I) + \frac{C - A - B}{\text{CM}(2)} \]

Metal node 3 is centered at the junction between the heater and the regenerator manifold. It includes half the heater and half the regenerator manifold. Pertaining to it are thermal conductance KME(3) already defined and KME(4) along the regenerator manifold. Thus:

\[ \text{KME}(4) = \text{KN} \times \pi \times \text{DIRM} \times \text{WTRM} \times \text{NTRM/IRM} \]

The heat capacity of this metal node involves the other half of the heater metal volume already calculated as X and half of the regenerator manifold metal volume. Thus:

\[ Y = \pi \times \text{DIRM} \times \text{WTRM} \times \text{NTRM} \times \frac{\text{LRM}}{2} \]

Thus the nodal heat capacity is:

\[ \text{CM}(3) = (X + Y) \times 5.00 \]

In this node the heat gain by conduction from metal node 2 is already calculated as A. The heat gain due to flame heating is already calculated as C. The heat loss by conduction to metal node 4 is:

\[ B = \text{KME}(4) \times (\text{TM}(3, I) - \text{TM}(4, I)) \times \text{DDT} \]

Therefore, by a heat balance

\[ \text{CM}(3) \times (\text{TM1}(E, I) - \text{TM}(3, I)) = A + C - B \]

Thus, the new temperature of metal node 3 after one time step's worth of conduction and external heat transfer is:
\[ TM1(3,I) = TM(3,I) + \frac{A + C - B}{CM(3)} \]

\[ F = +KME(4) \times (TM(3,I) - TM(4,I)) \times DDT \]

\[ TM1(4,I) = TM(4,I) + \frac{A - R}{CM(4)} \times DDT \]

Metal node 4 is centered at the hot end of the regenerators attached to each cylinder. It includes the heads of the regenerators, half of the regenerator manifolds, and one quarter of the regenerator matrix and one quarter of the regenerator wall. Pertaining to it are thermal conductance KME(4), already defined, as well as KME(5) between the hot end and the middle of the regenerator. Thus:

\[ KME(5) = KH \times PI \times DR \times RWT \times NR \times (LR/2) \]

\[ + KMX \times PI_4 \times DR \times 2 \times NR \times (LR/2) \]

The heat capacity of the metal node involves the other half of the regenerator manifold volume already calculated as \( Y \). The volume of the regenerator heads is:

\[ X = PI_4 \times (DR + RWT) \times 2 \times TRH \times NR \]

and \( Z \) the metal volume of the regenerator and surrounding cylinder wall. Thus:

\[ ZZ = PI \times DR \times RWT \times LR/4 + PI_4 \times DR \times 2 \times LR/4 \times FF \]

Thus, the nodal heat capacity is:

\[ CM(4) = (Y + X + ZZ) \times 5.00 \]

In this node the heat gain by conduction from node 3 is already calculated as \( B \). The heat loss by conduction to the middle of the regenerator is:

\[ A = KME(5) \times (TM(4,I) - TM(5,I)) \times DDT \]

There is no external heat transfer in this node. By heat balance

\[ CM(4) \times (TM1(4,I) - TM(4,I)) = B - A \]

Thus, the new temperature of metal node 4 after one time step's worth of conduction is:

\[ TM1(4,I) = TM(4,I) + \frac{B - A}{CM(4)} \]

Metal node 5 is centered at the center of the regenerator and includes the middle half of the regenerator. Pertaining to it are thermal conductances KME(5) between the hot end and the middle of the regenerator and KME(6) between the middle and the cold end of the regenerator. Since dependence of thermal conductivity on temperature is being ignored, KME(6) = KME(5).
The heat capacity involves half the metal volume of the regenerator and surrounding cylinder wall. Thus, the heat capacity for this node is:

\[ C_M(5) = 2 \times ZZ \times 5.00 \]

The heat gain from the hot part of the regenerator is already calculated, A. The heat loss to the cold part of the regenerator is:

\[ B = KME(6) \times (TM(5,Y) - TM(6,Y)) \times DDT \]

By heat balance

\[ C_M(5) \times (TM(5,Y) - TM(5,Y)) = A - B \]

Thus, the new temperature of metal node 5 after one time step's worth of conduction is:

\[ TM(5,Y) = TM(5,Y) + \frac{A - B}{C_M(5)} \]

The value \( TM(6,Y) \) is always equal to TM1.

4.2.7.10 Index Metal Temperatures

At this point the new engine metal node temperatures, TM1(X,I) are transferred to the old metal node temperature TM(X,I) which is displayed. When the engine rotates, the metal temperatures TM(X,I) will be changed once again. However, this time new and old metal temperatures will not be needed.

4.2.7.11 Average Temperatures

Finally, average metal temperatures between the metal nodes must be calculated. These temperatures also become the gas node temperatures for the isothermal section of the engine.

4.2.8 Engine and Vehicle Control Subprogram (EVSC) Part 2

Part 2 does one thing. It tests flag IG1. If the engine should be stopped, it returns to the unified readout (see Section 4.2.4). If it should be
going, it goes on to the next section.

555 CONTROLL PROGRAM PART 2
556 C TEST FLAG TO DECIDE WHETHER TO GO ON TO NEXT SUBPROGRAM
557 IF (IG1-1) 401, 425, 425

4.2.9 Engine Torque and Internal Heat Transfer Subprogram

The engine calculation subprogram calculates the torque generated by the engine for the conditions of temperature and pressure in each of the four engine spaces and for the engine speed at the time. In order to speed up the calculations, the following simplifying assumptions are made:

1. The gas pressure in each engine space is uniform.
2. Internal heat transfer between the gas and the solid is perfect in the heater manifold, heater tubes, regenerator manifold, regenerator and cooler.
3. There is no heat transfer between the gas and the solid in the hot space and in the cold space and in the cold manifold.
4. The regenerator metal temperature is initially assumed to be linear, but during operation the midpoint metal temperature is adjusted so that the net heat transfer to the regenerator (metal node 5) is zero.
5. The metal in both the heater manifold and the regenerator manifold is assumed to have linear temperature gradients.

The calculations in this subprogram proceed in the following steps. Each will be explained as needed followed by the applicable program segment.

Step 1 - Calculate New Engine Volumes

The engine volumes for each compartment depend upon the engine angle EARAD. This angle is determined from the last engine position and the angle increment, DANG, derived from a torque balance and assessment of acceleration. This step gives all the variable volumes for the four working spaces and the total volumes for each working space. Figure 4.14 shows the spacing between the cold end of each cylinder and the cold end of each piston for somewhat more than one cycle. Note that at 0 degrees, cylinder 1 (X1) has the power piston at the cold end. Then at 90° engine angle, cylinder 4 has minimum cold space. At 180° cylinder 3 has minimum cold space. At 270° cylinder 2 has minimum cold volume.

In the Siemens arrangement which is used in the 4L23 engine as well as all the United Stirling machines, the hot end of one cylinder is connected to the cold end of the next through the heater, regenerator and cooler. Figure 4.4 and Table 4.3 shows how they are connected.

Daniele and Lorenzo (4) have indicated that gas can only be added to or removed from each working space through a timing slot in the drive rod. For the purpose of this program it was assumed that these timing slots would be full open 45° before and 45° after bottom dead center. This is the reason for the addition, removal schedule given in the explanation of the engine and vehicle control subprogram.
Figure 4.14. Volumes and Spacings in Engine.
Table 4.3

ENGINE SPACE Nomenclature

<table>
<thead>
<tr>
<th>Working Space Number</th>
<th>Hot Space Cylinder Number</th>
<th>Cold Space Cylinder Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>1</td>
</tr>
</tbody>
</table>

The quantities X1 to X4 graphed in Figure 4.14 are calculated from the formula for a crank operated piston (5). From these the variable volumes in the hot space, VHA(X, Y), and in the cold space, VCA(X, Y) are calculated.

Finally, in Step 1 the cumulative volumes are calculated from the variable and fixed volumes. Each cumulative volume is calculated from the hot end of the engine to a particular point in the engine. (See the nomenclature.) Volumes recorded this way are needed later in the calculation.
Step 2 - Calculate Effect of Control

In this version of the program the control method is by adding or removing gas. The control subprogram computed a new pressure, PX, for a particular working space, IG3. (See lines 856-879.) Step 2 calculates the effect of this action on the engine torque and heat transfer.

The first thing is to calculate Y, the ratio of the volume now occupied by the gas originally in the working space for which pressure has been adjusted. This is done assuming the total volume is adiabatic. Next X, the volume of gas added, is calculated. If X is negative, gas has been removed.

586 C STEP 2--CHANGE IN GAS VOLUMES. TEMPERATURES AND GAS NODE INVENTORIES
587 C OF WORKING SPACE THAT CAN HAVE ITS GAS INVENTORY ADJUSTED X=
588 C VOLUME OF GAS ADDED(+) OR REMOVED(--) AT CURRENT PRESSURE AND TEMP
589 C FOR THAT WORKING SPACE
590 Y=(P1(IG3).PX)**KR
591 X=VT(1 IG3)+(1-Y)

If gas has been added, then the temperature of the added gas is first calculated by assuming that the gas enters at cooling water temperature, TWI, and original pressure, P1(IG3) and then is compressed adiabatically to pressure PX. Next mass added, M2, is calculated from the perfect gas law. This pressure change affects all gas node temperatures for the adjusted working space since in this part of the calculation no heat transfer is allowed. Finally, the temperature of the cold space is adjusted because of the gas added.

592 C GAS INVENTORY CHANGE
593 IF(I.GG>102.101.101
594 C TEMP OF ADDED GAS
595 101 YY=TWI+(PX/P1(IG3))**GA
596 C MASS ADDED
597 M2=PX*X/(YYYY*DD)
598 C NEW TEMPERATURES DUE TO INVENTORY CHANGE
599 102 ZZ=(PX/P1(IG3))**GA
600 DO 807 K=1.8
601 807 TGA(K.IG3)=TGA(1. K.IG3)+ZZ
602 C ADJUSTMENT OF COLD SPACE TEMP. WITH GAS ADDITION
603 IF(X GT 0) TGA(1.8.IG3)=(TGA(1.8.IG3)*W(1.8.IG3)+YY*M2)/
604 1 (W(1.8.IG3)+M2)

After the old pressure P1(IG3) is utilized for everything it needs to be, it is updated to the new pressure PX.

605 C NEW PRESSURE DUE TO INVENTORY CHANGE
606 P1(IG3)=PX

Next the cumulative volumes and the gas node inventories for the working space which is having its pressure changed (IG3) must be adjusted. The process is different depending on whether gas is added or removed. If gas added (X is greater or equal to zero), the cumulative volume of all the gas nodes except the last are reduced by the factor Y which in this case is less than 1. The total volume, CVG(8,IG3) does not change. The gas masses 1 to 7 do not change since all the added gas goes into node 8.
If gas must be removed, any number of gas nodes can be removed and the remaining nodes can expand to take up the space. In this case Y, the volume ratio is greater than 1. Each cumulative volume is expanded by this ratio. However, when the cumulative volume CVG(K,IG3) first becomes greater than the total volume for that working space, CVM(8,IG3), then the mass of gas in this node is reduced depending upon the volume of this node still in the working space (lines 620 and 621). The total cumulative volume for that interpolated node becomes the total volume (line 625). Flag ZZ is used to make all subsequent gas nodes to have zero mass (line 624) and a cumulative gas volume equal to the total gas volume.

Finally, the new total mass for the working space must be re-added.

For the case of gas being added the new value of M(IG3) has been calculated in line 597.

Step 3 - Volume Change--No Heat Transfer

In this method of analysis the process which occurs in the engine simultaneously is broken up into equivalent sequential steps. These are:

Step 3 - Volume Change with No Heat Transfer. Find the volumes of the gases that originally occupied each engine space before the volume change in Step 1. Find the temperature that each of the original nodes of gas now has due to an adiabatic expansion or compression.
Step 4 - Redefine the gas nodes due to gas flow. Find the mass and the mass average temperature of the gas now occupying each one of the gas spaces.

Step 5 - Allow heat transfer to take place in each one of the gas spaces if it is supposed to. To simplify calculation in this program, the hot and cold variable volume spaces are assumed to have no heat transfer and the other spaces are assumed to have perfect heat transfer. The heat transferred in each node goes to change the temperature of the metal nodes or is absorbed by the cooling water. No gas flow between nodes is allowed during this step so the heat capacity at constant volume is the proper one to use for the gas.

Step 6 - Due to heat transfer in Step 5 each node will have a different pressure. Step 6 calculates those pressures.

Step 7 - The fictitious barriers that have separated the nodes during Steps 5 and 6 are now removed. All gas nodes in each working space are allowed to come to a common pressure again. Step 7 calculates this common pressure.

Step 8 - The process of adiabatic pressure equilibration in Step 7 changes the temperature in each gas node. Step 8 calculates these final gas temperatures and prepares the calculation to start through for another time step.

Now that the overall process has been explained, Step 3 will now be explained in detail.

The temperature-volume relationship for an adiabatic process is:

\[
\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{k-1}
\]

In the calculation CVG(8,I) is the original total volume for the Ith working space and CVM(8,I) is the new total volume as calculated in Step 1, line 584. After the new temperatures are calculated (line 639), all the cumulative gas volumes are adjusted proportional to the total gas volume change (line 642).
Step 4 - Computation of Mass Average Temperature and Mass of Gas Now in Each Engine Space Due to Gas Flow

Because of the volume changes and the adiabatic temperature changes like those shown in Figure 4.14 and because of gas inventory changes for control, there is mass flow.

It was found by experience that because of gas inflow for control that the programming must be able to handle mass flow across any number of nodes. That is, during one time step so much gas can be added to the cold space to push all the original gas into the hot space.

One of the important features of the program that was used as a model for this program was that the temperature was to vary linearly inside the gas nodes that were originally in the dead volumes of the engine. This idea was programmed and debugged but it was found that after several time steps, situations would develop which would result in a negative mass being assigned to a gas node which would result in a negative absolute pressure for that node. Since flow through several nodes during one time step will create certain inaccuracies, it was decided to simplify the programming and have all the gas in each gas node have an average temperature instead of a linear temperature gradient.

In order to be able to handle mass flow across any number of nodes, it was necessary to have a nomenclature where the volumes of the gas spaces are expressed as cumulative volume from the hot end. For instance, $CVM(2,1)$ is the cumulative volume from the hot end to the interface between the heater manifold and the heater for the $I$th working space. (See Figure 4.15.) The metal node temperatures $TM(1,1)$ to $TM(6,1)$ have already been discussed. $TM(6,1)$ is fixed at the cooling water temperature $TMI$. All the other metal nodes float in temperature due to heat transfer by conduction and convection. During Step 4 it is convenient to define an average metal temperature for each part of the working space that transfers heat. For this purpose $TMA(2,1)$ to $TMA(7,1)$ are defined as midway between the metal node temperatures (see Figure 4.15).

At the start of the time step the gas nodes shown in Figure 4.15 all have the same volumes as the metal nodes. Up until now the mass in all these gas nodes has not changed except addition or removal of gas for control. (See Step 2.) However, because of motion of the pistons and gas inventory change, flow has taken place. During the time step up till now no heat transfer has taken place between the working gas and the metal so the temperature of the gas nodes will now be different from the metal nodes. In Figure 4.15 an adiabatic compression is assumed so that the temperature of all gas nodes is higher. However, the general shape of the temperature distribution is retained. For instance, in this particular program, the gas originally at $TMA(2,1)$ attains the temperature $TGA(1,2,1)$. (See Step 3.) Now with the cumulative volumes in arrays and the temperatures also in arrays one can program a general case that will determine the mass of gas in each engine space after mass flow and the mass average temperature of that gas.

To start out the programming one must start the main do loop for the four working spaces.
Figure 4.15. Nomenclature for Step 4.
Next, two flags are initialized to 1. The K flag keeps track of the solid nodes and the L flag, the gas nodes. This arrangement is needed so that any number of gas nodes can be packed into a solid node or a gas node can be spread out over many solid nodes if required.

Then the gas inventory array at the end of the time step \( W(2, X, I) \) and the average gas temperature array at the end of the time step are zeroed.

In apportioning the masses it was found that the first time through a particular part of the program was different than the next time. Therefore, a second time flag was found necessary. This is initialized.

For each working space we start with the first gas node and the first metal node. We keep adding nodes to the one with the least volume until both gas and metal have 8 nodes. When this is so, the program for that working space is complete. The decision point compares the cumulative volume in the gas for \( L \) nodes to the cumulative volume in the engine metal for \( K \) nodes. The cumulative gas volume can be less than exactly equal to or greater than the cumulative metal volume.

Now the three possible cases will be discussed in the order they appear in the program. We will first discuss the case when the cumulative gas volume is less than the cumulative metal volume. For instance, take the case where \( K = 1, L = 1 \) and \( II = 1 \), initial case with gas compression.
In this case, \( Y = W(2, K, I) = 0 \). The new average temperature \( TGA(2, K, I) \) is simply \( TQA(1, L, I) \). The \( L \) or gas index is incremented. If \( L \) is greater or equal to 9, the solution is completed. If not, the solution returns to the top of the decision tree (line 659).

660  C**** CUM. GAS VOL. LESS THAN CUM. METAL VOLUME.
661  345  IF(II)254, 354, 355
662  354  II=1
663  355  W(2, K, I)=PM
664  TGA(2, K, I)=TQA(1, L, I)
665  GOTO258
666  355  Y=W(2, K, I)
668  TGA(2, K, I)=TGA(2, K, I)+Y+TQA(1, L, I)+W(1, L, I)+Y+TGA(1, L, I)
669  358  CONTINUE
670  C INDEX GAS NODE FLAG AND RETURN
671  L=L+1
672  C CHECK FOR END OF MASS FLOW CALCULATION
673  IF(L GE 9) GOTO 310
674  C RETURN
675  GOTO 748

If the next time through the cumulative volume of the gas is still less than the metal space it is filling, in this case the hot space, the calculation still goes through the same parts of the program.

Now this time through \( W(2, K, I) \) is the mass of gas in the hot space with the first two gas nodes being considered. \( TGA(2, K, I) \) is the average temperature in the hot space so far.

The other half of the programming given above (lines 659-663) cannot be entered from the beginning of the calculation. During the calculation, addition of a metal node makes the metal node cumulative volume greater than the gas node cumulative volumes.

\[ \text{CVG}(L=2, I) \]
\[ \text{CVM}(K=1, I) \]

[Diagram]

\[ \text{CVG}(L, I) \]
\[ \text{CVM}(K-1, I) \quad \text{CVM}(K, I) \]
When this happens, the flag II is set to zero (see line 723) and the calculation enters this other part of the program. A new mass \( W(2,K,I) \) starts to be accumulated by the addition of residual mass or the gas mass hanging over when the gas in node \( K-1 \) was completely calculated. The average gas temperature calculation is also initiated with the temperature of gas node \( L \). \( L \) is indexed by one and the calculation may come back through again.

If the next gas node still makes \( CVM(K,I) > CVG(L,I) \) as in the sketch below, then the calculation goes back through lines 666-669 because now \( II = 1 \). That is, it is the second time for the new metal volume node. This programming adds to the calculation of the mass and the average temperature in a particular engine volume but never finishes it.

The cumulative volumes may sometimes be exactly equal during the calculation. Quite often when both \( K \) and \( L \) are 9, the cumulative volumes will match exactly. Generally, this programming is the same as previous programming. The first time flag is set to 1 and both \( K \) and \( L \) flags are indexed. The calculation is ended if \( K \) or \( L \) are greater or equal to 9. In most cases both would be 9.

```plaintext
603 CVG(L-1,I) CVG(L,I)
604 CVM(K-1,I) CVM(K,I)
```

```plaintext
600 CVG(L-1,I) CVG(L,I)
601 CVM(K-1,I) CVM(K,I)
```

The cumulative volumes may sometimes be exactly equal during the calculation. Quite often when both \( K \) and \( L \) are 9, the cumulative volumes will match exactly. Generally, this programming is the same as previous programming. The first time flag is set to 1 and both \( K \) and \( L \) flags are indexed. The calculation is ended if \( K \) or \( L \) are greater or equal to 9. In most cases both would be 9.

```plaintext
600 CVG(L-1,I) CVG(L,I)
601 CVM(K-1,I) CVM(K,I)
```
The final possibility is that the cumulative gas volume can be greater than the cumulative metal volume. The way the programming was done there is a special case when \( K \leq 1 \) and a general case.

For the special case as shown below, the mass \( w(2,K,I) \) is a fraction of \( w(1,L,I) \) based upon the volumes. The average gas temperature is transferred over directly. The residual mass is that hanging over. The second time flag II is set to zero and \( K \) is indexed by one.

```
688 C***** CUM GAS VOL. GREATER THAN CUM METAL VOLUME
689 747 IF( K = 1 AND L EQ 1 ) GOTO 758
700 GOTO 701
701 C FIRST NODE FOR GAS AND METAL
702 750 W(2,K,I) = W(1,L,I) * CVMK(1,I) / CVG(1,I)
703 TGRA(2,K,I) = TGRA(1,I)
704 RM = W(1,L,I) - W(2,K,I)
705 GOTO 708
706 C GENERAL CASE
707 C CHECK FIRST TIME FLAG
708 751 IF(CF1 EQ 14) GOTO 744
709 C FIRST TIME FOR NEW GAS NODE
710 744 P = CVMK(1,I) / CVG(1,I)
711 RM = RM - P * W(1,L,I)
712 W = W(2,K,I)
713 W(2,K,I) = W(2,K,I) + P * W(1,L,I)
714 TGRA(2,K,I) = TGRA(1,I) + W * TGRA(1,I) / CVG(1,I)
715 GOTO 706
716 C AFTER THE FIRST TIME
718 747 W = W(2,K,I) + P * W(1,L,I) / CVG(1,I)
719 RM = RM - W(2,K,I)
720 W = W(2,K,I)
721 TGRA(2,K,I) = TGRA(1,I)
722 C RESET FIRST FLAG ON GAS VOLUME SHORT TIME
723 757 II = 0
724 C INDEX SOLID NODE FLAG
725 RES = 1
726 C CHECK FOR END OF FLOW CALCULATION
727 IF( GE 99) GOTO 718
728 C RETURN
729 GOTO 748
```

![Diagram](image-url)
Now for the next node $K = 2$ and $L = 1$ and $II = 0$.

Therefore, it would go through lines 717-721. $RR$ is the fraction of the residual volume that is assignable to $W(2,K,I)$. Therefore, a new residual mass, $RM$, is calculated for that still hanging over. Gas temperature is transferred across.

During the course of the calculation, indexing of $L$ leads to the case where $CVG(L,K) > CVM(K,I)$. Thus:

In this case (lines 709-716) $RR$ is the fraction of $W(1,L,I)$ that it takes to finish $W(2,K,I)$. The rest is made the residual mass. The final average gas temperature is calculated for that node using the mass and the average temperature up to that point and the new mass and average temperature.

With all this complicated programming for transferring masses during Step 4, there were many chances for error. Therefore, an error trapping routine is introduced at this point which will stop the program and print out some intermediate results if mass is changed during this step. All the masses are summed and compared with the previous mass sum. If the total mass is off by more than 0.1 gram, then it will write out the flow error and the working space it has occurred in. Other intermediate values are printed out to show the operator what the problem is. See the operator manual (Section 6) for additional details. This error tracking program was very useful in the debugging of this program.
Step 1 - Change in Temperature of Gas and Metal Nodes Due to Heat Transfer with No Volume Change

Note again that metal nodes 1 to 5 float. That is, as they receive heat their temperature rises; as they lose heat their temperature falls. Also, note again that it is assumed that the gas in the heater manifold, heater, regenerator manifold, regenerator and cooler attains the temperature of the metal during this step. To simplify calculation the amount of heat transferred to each metal node is calculated first. Then the metal node temperatures are adjusted according to their heat capacity.

The heat transferred by changing the gas temperature to the average temperature of the heater manifold is assumed to be transferred half to metal node 1 and half to metal node 2. The amount of heat transferred is based upon the gas mass flow between the metal node points. The heat capacity of this gas is taken at constant volume. For instance, the temperature drop for node 1 is from the temperature of the gas calculated to be in the heater manifold at the end of Step 4 and to the average temperature of metal nodes 1 and 2.

The heat received (or given up) by the other metal nodes is computed similarly. Note that this is being done for the heat working spaces.
C HEAT RECEIVED BY METAL NODE 5
Y = CV*W(2, 6, I) + (TGA(2, 6, I) - TMA(6, I)) / 2.

C HEAT RECEIVED BY METAL NODE 6
Y = CV*W(2, 7, I) + (TGA(2, 7, I) - TMA(7, I)) / 2.

C HEAT RECEIVED BY METAL NODE 7
Y = CV*W(6, I) + (TGA(6, I) - TMA(6, I)) / 2.

Next, it is now assumed that the gas in each space of each compartment except
the gas in the adiabatic spaces attains the average temperature of the metal
in that space.

C CHANGE IN AVERAGE GAS TEMPERATURES DUE TO HEAT TRANSFER
DO 360 K = 1, 7
360 TGA(2, K, 1) = TMA(K, 1)

Finally, the metal node temperatures are changed due to heat transfer between
the working gas and the metal.

C CHANGE IN METAL NODE TEMPERATURES DUE TO HEAT TRANSFER
DO 382 K = 1, 5
382 TMA(K, 1) = TMA(K, 1) + CV*W(0, 1)
CONTINUE
CONTINUE

Step 6 - New Pressures for Each Space Due to Heat Transfer with No Volume
Change

The gas temperature changes in Step 5 were done with each gas node isolated.
Therefore, each gas node will have a different pressure. In Step 6 these
pressures are calculated using the perfect gas law.

C STEP 6 - NEW PRESSURES FOR EACH SPACE DUE TO HEAT TRANSFER WITH NO
VOLUME CHANGE
DO 360 K = 1, 4
360 P(K) = CV*W(K) + TGA(K, 1) / CV*W(K)
CONTINUE
CONTINUE

C HEATER MANIFOLD
P(K) = CV*W(K, 1) + TGA(K, 2) / CV*W(K)
CONTINUE

C REGENERATOR MANIFOLD
P(K) = CV*W(K, 1) + TGA(K, 2) / CV*W(K)
CONTINUE

C REGENERATOR HOT HALF
P(K) = CV*W(K, 2) + TGA(K, 3) / CV*W(K)
CONTINUE

C REGENERATOR COLD HALF
P(K) = CV*W(K, 2) + TGA(K, 3) / CV*W(K)
CONTINUE

C COOLER
P(K) = CV*W(K, 2) + TGA(K, 3) / CV*W(K)
CONTINUE

C COIL SPACE
P(K) = CV*W(K, 2) + TGA(K, 3) / CV*W(K)
Step 7 - Adiabatic Pressure Equilibration at Constant Total Volume

Now in Step 7 the barriers between the nodes are removed. Assuming adiabatic processes, it is possible to solve algebraically for a common pressure for all the nodes. Start with the adiabatic relationship

$$\frac{P_2}{P_1} = \left(\frac{V_1}{V_2}\right)^k, \quad k = \frac{C_P}{C_V}$$

Using the nomenclature of the program the gas originally in the hot space now has a volume of

$$V_1(I) = V_{HA}(2,K) \times (F3(I,1)/F4(I)) \times KR$$

The gas originally in the heater manifold now has a volume of

$$V_2(I) = V_{HM} \times (F3(I,2)/F4(I)) \times KR$$

The heater:

$$V_3(I) = V_{HD} \times (F3(I,3)/F4(I)) \times KR$$

The regenerator manifold:

$$V_4(I) = V_{RM} \times (F3(I,4)/F4(I)) \times KR$$

The hot half of the regenerator:

$$V_5(I) = V_{HD}/2 \times (F3(I,5)/F4(I)) \times KR$$

The cold half of the regenerator:

$$V_6(I) = V_{CD}/2 \times (F3(I,6)/F4(I)) \times KR$$

The cooler:

$$V_7(I) = V_{CD} \times (F3(I,7)/F4(I)) \times KR$$

The cold space:

$$V_8(I) = V_{CA}(2,1) \times (F3(I,8)/F4(I)) \times KR$$

Now the total volume has not changed. Therefore:

$$V_T(I) = V_1(I) + V_2(I) + V_3(I) + V_4(I) + V_5(I) + V_6(I) + V_7(I) + V_8(I)$$

The unknown $F4(I)$ is solved for in the above equations. See the programming below.
Step 7A - New Temperatures

This pressure equilibration step results in different temperatures for each gas node. Using the adiabatic relationship these temperatures are calculated.

Step 7B - New Volumes

With a new pressure and new temperatures, new gas node volumes and cumulative volumes are now calculated.

Finally, since CWG(8,1) by the above series of calculations may have an accumulated error, the correct value is substituted.

Step 8 - Initialize Quantities for Next Increment

Because of the way the calculation was formulated, the temperatures, volumes, pressures and masses in the four working spaces and in the eight nodes in each working space could not be modified as the calculation progressed. A difference had to be made between the old and new values. In this step these values are reinitialized. Note that Steps 6, 7 and 8 are in one do loop (lines 77 to 812). Therefore, these steps are done for working space 1, \( I = 1 \), and then for working space 2, \( I = 2 \), and so on.
Step 8 -- Initialize Quantities for Next Increment

DO 364 K = 1, 8
TGA(1, K, I) = TGA(2, K, I)

Volumes
VT(1, I) = VT(2, I)
VCA(1, I) = VCA(2, I)
VHA(1, I) = VHA(2, I)

Pressures
P1(I) = P4(I)

Masses
DO 750 K = 1, 8
W(1, K, I) = W(2, K, I)
CONTINUE

Step 9 -- Determine Engine Torque at Output Shaft

This step is the culmination of a large amount of calculation. It proceeds in three steps: 1) find the forces on the pistons, 2) find the torques and average pressure, 3) find the shaft torque from the indicated torque based upon a correlation.

The force on a particular piston is the net of three forces: 1) the pressure times the area of the hot end of the piston (ACY), 2) the pressure of the next working space times the area of the bottom of the piston (BCY) taking out for the drive rod, and 3) the pressure drop across the seal times the seal area (CCY). In this program the crank case pressure is fixed at 0.1 MPa = 1 atm. Since the pressures are in megapascals, \(10^6\) N/m², and the areas are in cm², a factor of 100 is needed to convert the units. Figure 4.16 shows that the forces on the pistons are all upward for a positive force.

Next, these forces are converted to a torque from each crank. The angle convention that is used in Figure 4.14. Note that since the radius of the crank, RC, is in centimeters, division by 100 is needed to obtain the torque in Newton-meters.

Torque on Each Crank: N-M. CCW is Positive

TCA(I) = RC(1, 100) – SIN(EPAD + EPI) + PI(I)
TCB(I) = RC(1, 100) – SIN(EPAD + EPI) + PI(I)
TCJ(I) = RC(1, 100) – SIN(EPAD + EPI) + PI(I)
TCG(I) = RC(1, 100) – SIN(EPAD + EPI) + PI(I)

Next, the indicated torque is the sum of the four crank torques. The average pressure is calculated to be used in the shaft torque calculation.
Figure 4.16. Force on Pistons and Engine Torque Calculations.
In order to avoid calculating flow losses all the way along, a correlation was made for the 4L23 engine to determine how the power drop due to flow losses correlates with engine pressure and speed. This correlation was based upon 16 cases run with the isothermal second-order analysis (6). This analysis was found to agree with the validated General Motors calculation to within 10% over the full range of engine operation (6). Appendix B fully explains this correlation and show that it is nearly exact.

4.2.10 Control Program (Part 3)
This very simply asks if time is up. If not, it starts over.

4.2.11 Final Summary Report
The final summary report is now very simple. It simply prints the total fuel consumed, the total time (given) and the ending vehicle speed. More information can be added as the need is felt.
5.0 LISTING OF PROGRAMS

Three separate computer codes are included in this report. One code, WARM, was used to evaluate how best to handle the burner and air preheater. This code is given in Appendix A along with an explanation of it and the results found from it.

Listings are given in this section for CNTLA.FOR and CNTLB.FOR. CNTLA contains the nomenclature for both programs. CNTLA.FOR is given on pages 73 to 86. CNTLB.FOR is given on pages 88 to 104. CNTLB.FOR was given piecemeal in Section 4 as the equations were explained.
FORTRAN SOURCE CODE LISTING

OF CNTLA
C PROGRAM CNTLA FOR
C WRITTEN BY MARTINI ENGINEERING UNDER CONTRACT NUMBER
C DENC-226 FOR NASA-LEWIS UNDER THE DOE ADVANCED AUTOMOTIVE
C PROPULSION PROGRAM. THIS PROGRAM SHOWS NOMENCLATURE FOR
C CNTLA AND CNTLB. CNTLA IS FOR CHANGING INPUT PARAMETERS
C FROM THE CONSOLE AND IS FOR CREATING A DATA FILE TO BE
C READ BY CNTLB.
C
***** NOMENCLATURE *****
A = TEMPORARY VARIABLE
AHF = HEAT TRANSFER AREA OF FULL AIR PREHEATER, SQ CM
ACE = PARTIAL ENGINE ACCELERATION, RAD/SEC**2
ACR = ANGLE INCREMENT CRITERIA, DEGREES
ACRP = ANGLE INCREMENT CRITERIA, RADIANs
ACV = ACCELERATION OF VEHICLE AT START OF TIME STEP, M/SEC**2
ACY = CI4*DCY**2
AF = AIR FRICTION, NEWTONs
AFAPF = AIR FLOW AREA FOR AIR PREHEATER, SQ CM
AFR = FRONTAL AREA OF VEHICLE TIMES SHAPE COEFFICIENT, M**2
AH = HEAT TRANSFER AREA FROM FLAME, FULL ENGINE, SQ CM
AHM = GAS HEATER MINIMUM FLOW AREA, CM**2
A = TEMPORARY VARIABLE
BCY = PI4*DCY**2
C = TEMPORARY VARIABLE
CF = CURRENT FUEL FLOW, G/S
CFH = FUEL FLOW ABOVE WHICH NEW HEAT TRANSFER FACTORS
      MUST BE CALCULATED, G/S
CFL = FUEL FLOW BELOW WHICH NEW HEAT TRANSFER FACTORS
      MUST BE CALCULATED, G/S
CM = METAL NODE HEAT CAPACITIES, J/K
CMH = HEAT CAPACITY OF GAS HEATERS FOR ONE CYLINDER, J/K
CMHAPF = HEAT CAPACITY OF AIR METAL NODE, J/K
CMH = HEAT CAPACITY OF REGENERATOR MATRIX, J/K
CP = HEAT CAPACITY AT CONSTANT PRESSURE, J/K
CPHP = HEAT CAPACITY OF AIR, J/K
CFAPF = HEAT CAPACITY OF FLUE GAS, J/K
CS = COEFFICIENT FOR SHAPE OF VEHICLE
CV = HEAT CAPACITY AT CONSTANT VOLUME, J/K
CVY = 4 +CZ+CT+CMPH
DANG = CHANGE IN ENGINE ANGLE, RAD
DCY = DIAMETER OF CYLINDER, CM
DCP = DIAMETER OF DRIVE POD, CM
DT = TIME STEP IN ENGINE CALCULATION TO MAKE DANG BETWEEN
      10 AND 10 DEGREES, SEC
DEO = EQUIVALENT DIAMETER USED IN AIR PREHEATER, CM
DIC = DIAMETER INSIDE OF COOLER TUBES, CM
DII = DIAMETER INSIDE OF HEATER TUBES, CM
DIH = INSIDE DIAMETER OF TUBES IN HEATER MAN, CM
DIHM = INSIDE DIAMETER OF TUBES IN REGEN MAN, CM
DIST = DISTANCE TRAVELED FROM START, M
DOH = OUTSIDE DIAMETER OF HEATER TUBES, CM
DF = DIAMETER OF EACH REGENERATOR, CM
DT = DISTANCE TRAVELED DURING TIME STEP, M
DTI = TIME STEP INITIAL AND STANDARD, SEC
DAS = ENGINE ANGLE DEGREES
DAPF = ENGINE ANGLE DEGREES
C EIN = ENGINE INERTIA, KG*M**2
C ERRFL = ERROR IN FLOW MASS BALANCE, GM
C EX(Y) = AIR PREHEATER METAL NODE TEMPS. AT START OF TIME STEP, K
C EY(Y) = AIR PREHEATER METAL NODE TEMPS. AT END OF TIME STEP, K
C FCA = FRACTION OF VCDX THAT IS ADIABATIC
C FF = FILLER FACTOR, FRACTION OF REGENERATOR VOLUME FILLED
C WITH SOLID, MUST BE ZERO IF IT IS NOT KNOWN
C FFF = FULL FUEL FLOW, G/S
C FLAME = BURNER FLAME TEMPERATURE, K
C FP(4) = FORCE ON PISTONS(AWAY FROM CRANKSHAFT IS POSITIVE)
C NEWTONS
C FUEL = TOTAL FUEL CONSUMED BY ENGINE, G
C FWI = FLOW, WATER INLET FOR ENTIRE ENGINE, G/SEC
C G = GAP BETWEEN HOT CAP AND CYLINDER WALL, CM
C QA = (KK-1)/KK
C GAPH = MASS VELOCITY (USED IN AIR PREHEATER), G/S CM**2
C OCT = GEAR CHANGE TIME, SEC
C GDF = GRAPHIC DISPLAY FLAG, SEC
C GDI = GRAPHIC DISPLAY INCREMENT, SEC
C QMAX = MAXIMUM MASS VELOCITY IN HEATER, G/S CM**2
C HAS = HEAT TRANSFER COEFFICIENT, W/K CM**2
C HCL = HOT CAP LENGTH, CM
C I = TEMPORARY INTEGER VARIABLE
C II = TEMPORARY INTEGER VARIABLE
C IG1 = FLAG 0-HEAT UP, 1-IDLE, 2-IN GEAR
C IG2 = FLAG 0=INITIAL VALUE, 1=AFTER CALC INITIAL GAS MASSES
C IG3 = FLAG SHOWING WORKING SPACE IN WHICH GAS MASS WAS CHANGED
C J = PRINTOUT FLAG--5 TO SCREEN, 2 TO PRINTER, INTEGER
C J1,12 = GRAPHIC OUTPUT, X VALUES
C IPV(2,4) = GRAPHIC OUTPUT ARRAY FOR PV DIAGRAM
C J1,J2 = GRAPHIC OUTPUT, Y VALUES
C JPV(2,4) = GRAPHIC OUTPUT ARRAY FOR PV DIAGRAM
C J7 = DETERMINES INPUT NUMBER SELECTION
C K = TEMPORARY INTEGER VARIABLE, SOLID INDEX COUNTER
C KAPH = THERMAL COND. FACTOR IN APH, W/K
C KAR = COEFFICIENT OF AIR RESISTANCE
C KK = CP/CV
C KM = THERMAL CONDUCTIVITY OF STRUCT. MAT., W/CM K
C KME(6) = THERMAL CONDUCTIVITY FACTOR FOR ENGINE METAL NODES W/K
C KMX = THERMAL CONDUCTIVITY OF MATRIX MAT., W/CM K
C KR = 1 / KK
C L = GAS INDEX COUNTER
C LAPH = HEAT TRANSFER LENGTH IN AIR PREHEATER, CM
C LC = LENGTH OF COOLER TUBES, CM
C LCR = LENGTH OF CONNECTING ROD, CM
C LH = LENGTH OF HEATER TUBES, CM
C LHM = LENGTH OF TUBES IN HEATER MANIFOLD, CM
C LHH = HEATED LENGTH OF HEATER TUBES, CM
C LHV = LOWER HEATING VALUE OF FUEL, KJ/G
C LR = LENGTH OF REGENERATOR, CM
C LRM = LENGTH OF TUBES IN REGENERATOR MAN., CM
C M(4) = INVENTORY OF GAS IN EACH ENGINE COMPARTMENT, G
C M2 = GAS MASS CHANGE, G
C ME = ENGINE MECHANICAL EFFICIENCY, PERCENT
C MGI = INITIAL GAS INVENTORY, G
C MIR = BASIC TIME CONSTANT IN ADDING OR REMOVING GAS
C MIR1 = ADJUSTMENT OF MIR TO PREVENT CONTROL OVERSHOOT
C MIV = MASS, INERTIA OF VEHICLE, KG
MM1 = MASS OF GAS MOVED ACROSS NODE 1 IN COLD DIRECTION
MM2 TO MM7 = SAME FOR NODES 2 TO 7
MH = MESH SIZE, WIRES/CM
MH1 = MOLECULAR WEIGHT OF WORKING GAS, G/G MOLE
MHFG = MOLECULAR WEIGHT OF FLUE GAS, G/G MOLE
N = NUMBER OF NODES IN AIR PREHEATER. INTEGER
NAPH = # OF AIR PREHEATER FLOW PASSAGES IN EACH DIRECTION
NFR = FLAG TO COUNT NUMBER OF CYCLES BEFORE PASSING PV DIAG
NGC = GEAR CHANGE FLAG, INTEGER
NO = NUMBER OF NODES IN AIR PREHEATER, REAL
NO2 = N/2
NP = NUMBER OF PEGENERATORS/CYLINDER
NS = NUMBER OF SCREENS PER PEGENERATOR
NTE = NUMBER OF COOLER TUBES/CYLINDER
NTH = NUMBER OF HEATER TUBES PER CYLINDER
NTPH = NUMBER OF TUBES IN PEGENERATOR MANIFOLD
OM1 = DESIRED IDLE SPEED OF ENGINE, R/S
OMEG = ACTUAL ENGINE SPEED, R/S
PAV = AVERAGE PRESSURE IN 4 CYLINDERS, MPa
PBIS = PROPORTIONAL BAND, IDLE SPEED, RAD/SEC
PBVS = PROPORTIONAL BAND, VEHICLE SPEED, M/SEC
PCF = PRESSURE-Flag, MPA
PI = PI = 3.141592654
PI4 = PI/4 = 1.570796327
PI2 = PI/2 = 1.570796327
PI4 = PI/4 = 0.7853981635
POE = PRINT OUT FLAG, SEC
PPI = HIGH PRESSURE RESERVOIR PRESSURE, MPa
PR = LOW PRESSURE RESERVOIR PRESSURE, MPa
PR4 = GAS PRESSURE OF WORKING SPACE HAVING ITS PRESS. ADJ. MPa
PS4 = GAS PRESSURE AT BEGINNING OF TIME STEP, MPa
PS4 = GAS PRESSURE AFTER VOLUME CHANGE, MPa
PS4 = GAS PRESSURE AFTER TEMPERATURE EQUILIBRATION AT
PS4 = CONSTANT VOLUME, MPA
PS4 = COMMON GAS PRESSURE AT END OF TIME STEP, MPA
QG = OUTPUT FLAG, 0=GRAPHICS ON SCREEN, REAL
QG = PRINTOUT FLAG, 0=TO SCREEN, 1=TO PRINTER
QG = OUTPUT FLAG, 0=PERIODIC PRINTOUT, 1=NONE
QG = HEATING OF HEATER TUBES OF ONE CYLINDER BY BURNER
QG = DURING A TIME STEP, J
QG = HEATING OF WORKING GAS IN HEATER TUBES DURING TIME STEP, J
QG = CUMULATIVE HEAT INPUT FOR CYCLE, J
QG = HEAT RECEIVED BY METAL NODES 1 TO 7 DURING STEP 5
QG = 0.8541 1.6 MOLE
QG = 0.017453 RADIANS/DEGREE
QG = PATIO OF AIR TO FUEL, G/G
QG = PATIO+1. G/G
QG = RADIUS OF CRANK, CM
QG = 2.4 PC
QG = PE = REYNOLDS NUMBER
QG = RE = NUMBER OF ENGINE REVOLUTIONS SINCE START
QG = FF = POLLING FRiction, NEWTONS
QG = WORKING GEAR PATIO, METERS/REV
QG = FIRST GEAR PATIO, VEHICLE TRAVEL/REV, METERS
QG = SECOND GEAR PATIO, VEHICLE TRAVEL/REV, METERS
QG = THIRD GEAR PATIO, VEHICLE TRAVEL/REV, METERS
RM = RESIDUAL MASS IN STEP 4, G
RR = RESIDUAL RATIO IN STEP 4
RT = INTERFACE TEMPERATURE IN STEP 4
RWT = REGENERATOR WALL THICKNESS, CM
RX = CP - CV
SPD = CRUISING SPEED OF VEHICLE, M/S
SPV1 = SPEED OF VEHICLE AT BEGINNING OF TIME STEP, M/SEC
SS = CHECK TO ALLOW USER CHANCE TO STOP
STN = STANTON NUMBER TIMES PRANDL NUMBER TO TWO THIRDS POWER
T1 = AMBIENT AIR TEMPERATURE, K
TA = AVERAGE OF HEATER METAL TEMPERATURES, K
TAC = VEHICLE ACCELERATION TIME, SEC
TAPH = THICKNESS OF PREHEATER PASSAGE, CM
TC = GAS TEMPERATURE AT REGENERATOR-COOLER BOUNDARY, K
TCR = DURATION OF STARTING MOTOR TORQUE, SEC
TCY = THICKNESS OF CYLINDER WALL, CM
TD = THMG-TWI
TE = ERROR IN CONTROLLED TEMP. OF HOT METAL, K
TG(X,Y,Z) = MATRIX OF GAS TEMPERATURES AT NODE BOUNDARIES
X=1 BEFORE MASS FLOW =2 AFTER
Y=1 MIXED TEMP. OF ADIABATIC HOT SPACES
Y=2 AT HOT END OF HEATER MANIFOLD
Y=3 AT INTERFACE BETWEEN HEATER MANIFOLD AND HEATER
Y=4 AT INTERFACE BETWEEN HEATER AND REGENERATOR MANIFOLD
Y=5 AT INTERFACE BETWEEN REGENERATOR MANIFOLD
Y=6 AT INTERFACE BETWEEN HEATER MANIFOLD AND REGENERATOR MANIFOLD
Y=7 AT MIDPOINT IN REGENERATOR
Y=8 IN COOLER
Z=1 TO 4 FOR 4 WORKING SPACES
TGA(X,Y,Z) = MATRIX OF AVERAGE GAS TEMPERATURES
X=1 BEFORE MASS FLOW =2 AFTER
Y=1 FOR HOT SPACES
Y=2 FOR HEATER MANIFOLDS
Y=3 FOR HEATERS
Y=4 FOR REGENERATOR MANIFOLDS
Y=5 FOR HOT HALF OF REGENERATOR
Y=6 FOR COLD HALF OF REGENERATOR
Y=7 FOR COOLER
Y=8 FOR COLD SPACES
Z=1,4 FOR 4 WORKING SPACES
TH = GAS TEMP. AT PEGEN MANIFOLD-REGENERATOR BOUNDARY, K
THC = THICKNESS OF HOT CAP CYLINDER, CM
THCH = THICKNESS OF HOT CAP HEAD, CM
THH = THICKNESS OF HOT CYLINDER WALL HEAD, CM
THW = THICKNESS OF WIRE IN SCREENS OF REGENERATOR, CM
THMG = TEMPERATURE, HOT METAL GOAL, K
THU = ENGINE WARM-UP TIME, SEC
TID = IDLE TIME AFTER CRANKING, SEC
T11 = THU+TCR
T12 = T11+TID
T13 = T12+TAC
TIM = CUM.ATIVE TIME, IEC
TIMX = SPECIFIC CUM.ATIVE TIME FLAG, SEC
TIN(20) = INLET AIR PREHEATER AIR NODE TEMP, K
TM(1,2) = METAL TEMP. AROUND HOT SPACE, K
\[ \begin{align*}
T_{\text{M}1} &= \text{METAL TEMP BETWEEN HEATER MAN AND HEATER, K} \\
T_{\text{M}2} &= \text{METAL TEMP BETWEEN HEATER AND REGEN MAN, K} \\
T_{\text{M}3} &= \text{METAL TEMP BETWEEN REGEN MAN AND PEGEN, K} \\
T_{\text{M}4} &= \text{METAL TEMP MIDPOINT OF REGENERATOR, K} \\
T_{\text{M}5} &= \text{METAL TEMP BETWEEN PEGEN AND COOLER, K} \\
T_{\text{M}6} &= \text{METAL TEMP BETWEEN COOLER AND COLD SPACE, K} \\
\text{T}_{\text{M\text{PH}}} &= \text{THICKNESS OF METAL SEPARATING EACH FLOW PASSAGE, CM} \\
\text{T}_{\text{EN}} &= \text{NET ENGINE TORQUE, N-M} \\
\text{T}_{\text{SET}} &= \text{TOTAL SIMULATION TIME, SEC} \\
\text{T}_{\text{0(20)}} &= \text{AIR PREHEATER FLUE GAS NODE TEMP, K} \\
\text{T}_{\text{PB}} &= \text{TEMPERATURE, PROPORTIONAL BAND IN HOT METAL, K} \\
\text{T}_{\text{OF}} &= \text{TORQUE FROM EACH PISTON, CCW IS POSITIVE, N-M} \\
\text{T}_{\text{OI}} &= \text{TOTAL INDICATED TORQUE, N-M} \\
\text{T}_{\text{0S}} &= \text{TOTAL SHAFT TORQUE, N-M} \\
\text{T}_{\text{OV}} &= \text{TORQUE VEHICLE PUTS ON ENGINE, N-M} \\
\text{T}_{\text{AV}} &= \text{AVERAGE REG. METAL TEMP, K} \\
\text{T}_{\text{EP}} &= \text{TIME INTERVAL FOR REPORT PRINTOUT, SEC} \\
\text{T}_{\text{PH}} &= \text{THICKNESS OF REGENERATOR HEAD, CM} \\
\text{T}_{\text{ST}} &= \text{STARTING MOTOR TORQUE, N-M} \\
\text{T}_{\text{T}} &= \text{CHECK TO DETERMINE WHEN POINTS SHOULD BE PLOTTED} \\
\text{THI} &= \text{TEMPERATURE, WATER INLET, K} \\
\text{THO} &= \text{TEMPERATURE OF COOLING WATER, K} \\
\text{TXM1} &= \text{TEMP-MASS PRODUCT FOR GAS MOVING PAST NODE 1} \\
\text{TXM2} &= \text{SAME FOR NODES 2 TO 6} \\
\text{U}_{\text{APH}} &= \text{HEAT TRANSFER COEFF. AIR TO METAL IN AIR PREHEATER, W/CM^2 K} \\
\text{U}_{\text{H}} &= \text{HEAT TRANSFER COEFF. FLUE GAS TO GAS HEATER METAL, W/CM^2 K} \\
\text{U}_{\text{XX}} &= \text{LAPL*AIR*PH*PH^*PH^/4*RAF*CPA} \\
\text{U}_{\text{XY}} &= \text{LAPL*AIR*PH*PH^*PH^/4*C2} \\
\text{V}_{\text{1}} &= \text{VOLUME OF GAS MOVED TOWARD COLD END AT NODE 1, CM^2} \\
\text{V}_{\text{2}} &= \text{SAME FOR NODES 2 TO 7} \\
\text{V}_{\text{AB}} &= \text{VOLUME OF AIR IN BURNER, CU CM} \\
\text{V}_{\text{CA(2,4)}} &= \text{VOLUME, COLD, ADIABATIC, START AND END OF TIME STEP} \\
\text{V}_{\text{CA1(4)}} &= \text{VOLUMES OF GAS ORIGINALLY IN ADIABATIC COLD SPACE} \\
\text{V}_{\text{CD(4)}} &= \text{VOLUMES OF GAS ORIGINALLY IN GAS COOLER AND} \\
\text{V}_{\text{CD(X)}} &= \text{ISOTHERMAL PART OF COLD DUCT AFTER VOLUME CHANGE} \\
\text{V}_{\text{CD(X)}} &= \text{VOLUME, COLD DEAD NOT IN GAS COOLER, CU CM} \\
\text{V}_{\text{HA(2,4)}} &= \text{VOLUME, HOT ADIABATIC, START AND END OF TIME STEP} \\
\text{V}_{\text{HAL(4)}} &= \text{VOLUMES OF GAS ORIGINALLY IN HOT ADIABATIC SPACE} \\
\text{V}_{\text{HD(4)}} &= \text{VOLUME CHANGE, CU CM} \\
\text{V}_{\text{VHD}} &= \text{VOLUME OF AIR IN BURNER, ASSUMED ISOTHERMAL, CU CM} \\
\text{V}_{\text{VHD1(4)}} &= \text{VOLUMES OF GAS ORIGINALLY IN HOT DEAD SPACE AFTER} \\
\text{V}_{\text{VHM}} &= \text{HEATER MANIFOLD DEAD VOLUME, CU CM} \\
\text{V}_{\text{VHM}} &= \text{VOLUME CHANGE, CU CM} \\
\text{V}_{\text{VHD(X)}} &= \text{VOLUME OF AIR IN BURNER, ASSUMED ISOTHERMAL, CU CM} \\
\text{V}_{\text{VHD1(4)}} &= \text{VOLUMES OF GAS ORIGINALLY IN HOT DEAD SPACE AFTER} \\
\text{V}_{\text{VHM}} &= \text{HEATER MANIFOLD DEAD VOLUME, CU CM} \\
\end{align*} \]
VIN = VEHICLE INERTIA AS SEEN AT CRANK SHAFT, KG*M**2
VRD = VOLUME, REGENERATOR DEAD, PER CYLINDER, CU CM
VRD1(4) = VOLUMES OF GAS ORIGINALLY IN REGENERATOR AFTER VOLUME
CHANGE, CU CM
VRM = REGENERATOR MANIFOLD DEAD VOLUME, CU CM
VSP2 = VEHICLE SPEED TO CHANGE TO SECOND GEAR, M/SEC
VSP3 = VEHICLE SPEED TO CHANGE TO THIRD GEAR, M/SEC
VT(2,4) = TOTAL GAS VOLUMES AT START AND END OF TIME STEP, CU CM
VT0 = TOTAL DEAD VOLUME, CU CM
W(X,Y,Z) = ARRAY OF NODAL GAS MASSES
X=1 BEFORE MASS FLOW =2 AFTER
Y=1 ADIABATIC HOT SPACES
Y=2 HEATER MANIFOLDS
Y=3 HEATERS
Y=4 REGENERATOR MANIFOLDS
Y=5 HOT HALF OF REGENERATORS
Y=6 COLD HALF OF REGENERATORS
Y=7 COOLERS
Y=8 ADIABATIC COLD SPACES
Z=1,4 FOR 4 WORKING SPACES
WAPH = WIDTH OF EACH AIR PREHEATER PASSAGE, CM
WRG = MASS OF REGENERATOR GAS MOVING INTO COOLER, G
WRH = MASS OF REGENERATOR GAS MOVING INTO HEATER, G
WTHM = WALL THICKNESS OF TUBES IN HEATER MAN, CM
WTPM = WALL THICKNESS OF TUBES IN PEGEN MAN, CM
X = TEMPORARY VARIABLE
X1 = ENGINE SPACINGS IN 4 CYLINDER MACHINE
X2 = 
X3 = 
X4 = 
X9 = EXP(UXX/CYY), ZERO FOR SLOW AIR FLOW THROUGH PREHEATER
XA = LCR**2
XB = LCR - RC
XC = R / MW
XDV = HORIZONTAL SCALE FACTOR FOR PV PLOT, CM**2
XH = HEAT TRANSFER FACTOR FOR GAS HEATERS
XLOW = HORIZ ZERO SUPRESSOR FOR PV PLOT, CM**2
XX(4) = OLD, NEW VOLUME RATIO
XT(4) = OLD, NEW TEMPERATURE RATIO
XY = HEAT TRANSFER FACTOR FOR AIR SIDE OF APH
XZ = HEAT TRANSFER FACTOR FOR FLUE GAS SIDE OF APH
Y = TEMPORARY VARIABLE
YY = TEMPORARY VARIABLE
Z = FLAG FOR WORKING FLUID; 1 FOR H2, 2 FOR HE, 3 FOR AIR
ZZ = TEMPORARY VARIABLE
***** START OF PROGRAM *****

DIMENSION THM(4), TCM(4), THG(2, 4), TGC(2, 4), TGCS(2, 4),

1 P2(4), P3(4, 5), P4(4), M(4), FF(4), TQ(4), VHA(2, 4), VCA(2, 4),

2 VCR(4), VCD(4), VHA(4), VHD(4), VMD(4), VT(2, 4), XX(4),

3 W(2, 4), WGD(2, 4), WCD(2, 4), WC(2, 4), TGR(2, 4), P1(4),

4 TMR(4), OHI(4), T3A(4), CM(6), KME(6)

INTEGER Z

REAL LCR, LH, LR, MSH, MW, KK, KR, LC, M, ME, KRR, KAR, MGI

REAL LHH, LHV, MWFG, LAPH, MIR, MIR1, LHM, MIV, LR, KM, KMX

REAL NTRM, NTC, NS, NR, NTH, NTHM, IE1, NO, NAPH, KAPF, KME

C BASE CASE INPUT IN ORDER OF CHANGE TABLE

DATA THMG, TPB, TW1, FW1, OM1/922.2, 50. , 300. , 1575. , 40. /

DATA T1, DT, ME, 2, RGE1/300. , 5, 90. , 1, 0.54/

DATA NTHM, DIHM, FFF, THU, LHM/36. , 0.472, 4.85, 20., 7.95/

DATA TCR, TID, TAC, TOTT, SPM/1.0, 1.0, 30., 90., 22.4/

DATA RC, LCR, DCY, DDR, DIH/2.325, 13.65, 10.16, 4.06, 0.472/

DATA WTHM, NTH, VHDX, NP, DR/0.084, 35. , 11.59, 6. , 3.5/

DATA LR, FF, NS, MSH, THW/2.5, 0.2, 0. , 0.0, 0.0/

DATA VCDX, FCA, DIC, LC, NTC/196.02, 0.95, 0.115, 12.9, 312. /

DATA MIV, NTRM, DIRM, AFR, LR/1000. , 36. , 472.1, 12.7, 95.9/

DATA DOH, LHH, THAP, LAPH, WAPF/0.640, 25.58, 0.01, 10., 5. /

DATA TAPF, NAPF, PRL, PRH, WTRM/0.3, 50. , 0.5, 10., 0.084/

DATA THH, TRH, RWT, TCY, THC/15.0, 5.0, 41.1, 1.27, 0.381/

DATA G, HCL, KM, KMX, THCH/0.0406, 10000., 150. , 16.55, 8. , 46.432/

DATA THCH, TRH, RWT, TCY, THC/15.0, 5.0, 41.1, 1.27, 0.381/

DATA BT, MIR, RAFF, NO, LHV/0.640, 25.58, 0.01, 10. , 5./

DATA GCT, RGE2, RGE3, VSP2, VSP3/1.0, 1.0, 2.0, 4.47, 13.42/

DATA THCH, TRH, RWT, TCY, THC/15.0, 5.0, 41.1, 1.27, 0.381/

DATA 0.0406, 10.0. , 2.0, 0.017, 0.381/

DATA QU, Q2, Q3, EIN, PEIS/1., 2., 1., 50., 0.5, 0./

C DATA CONSTANTS

DATA PI4, PI, PI2, RAD, R/0.7854, 3.14159, 1.570796, 0.917453, .314/

DATA J, CPA, CPFG/5.1, 0.3, 1.20/

WRITE(J, 8006)

8006 FORMAT('DATA READ IN')

C INSTALL BASE CASE DATA OR DATA FROM FORT10.DAT

WRITE(5, 8010)

8010 FORMAT('TYPE 1 LEAVE IN BASE CASE DATA')

1 TYPE 2 TO BRING IN STORED DATA FROM LAST CASE)

READ(5, 8011)

8011 FORMAT(13)

IF(1-2)950, 960, 968

C READ IN DATA FROM LAST CASE

960 READ(10, 8004) THMG, TPB, TW1, FW1, OM1

READ(10, 8004) TI, DT, ME, RGE2, KAPF

READ(10, 8004) NTHM, DIHM, FFF, THU, LHM

READ(10, 8004) TCR, TID, TAC, TOTT, SPM

READ(10, 8004) RC, LCR, DCY, DDR, DIH

READ(10, 8004) WTHM, NTH, VHDX, NR, DR

READ(10, 8004) DOH, LHH, THAP, LAPH, WAPF

READ(10, 8004) VCDX, FCA, DIC, LC, NTC

READ(10, 8004) MIV, NTRM, DIRM, AFR, LR

READ(10, 8004) DOH, LHH, THAP, LAPH, WAPF

READ(10, 8004) TAPF, NAPF, PRL, PRH, WTRM

READ(10, 8004) THH, TRH, RWT, TCY, THC

READ(10, 8004) BT, MIR, RAFF, NO, LHV

READ(10, 8004) CMAPTH, AFAPF, PA1, CZ, DEQ

READ(10, 8004) UXX, DZ, CV, UXX, CVY

READ(10, 8004) FUEL, AMF, ANH, CNE, OEX

READ(10, 8004) KAP, TIN, VHD, VRD, CMX

READ(10, 8004) VCD, VCD, VTD, XA, XB

READ(10, 8004) ACY, BCY, P12, PC2, CCY
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031  C  NUMBER OF NODES IN ARP FIXED BECAUSE OF PROGRAM SIZE
032  GOTO9
035  111  NO-R
036  GOTO9
039  121  LRH=00
042  GOTO9
045  122  GHT=00
048  GOTO9
051  124  FGET=00
054  GOTO9
057  125  FGET=00
060  GOTO9
063  127  VFB=00
066  GOTO9
069  127  VFB=00
072  GOTO9
075  127  VFB=00
078  GOTO9
081  127  THH=00
084  GOTO9
087  127  TPH=00
090  GOTO9
093  129  RHT=00
096  GOTO9
100  130  GOTO9
103  131  GOTO9
106  131  GOTO9
109  131  GOTO9
112  131  GOTO9
115  131  THCH=00
118  GOTO9
121  137  GOTO9
124  154  HCL=00
127  GOTO9
130  155  HN=00
133  GOTO9
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211  198  GOTO9
214  199  GOTO9
217  200  GOTO9
220  201  GOTO9
93
HEAT CAPACITY OF AIR PREHEATER METAL ASSUMING STEEL WITH

5.00 J/CU CM K HEAT CAPACITY

CMAPH=LAPH+WAPH*2. *NAPH+TMAPH+5.00/NO

HEAT CAPACITY OF ENGINE METAL NODES

X=PI4+DCY**2. *(THH+THCH)
Y=PI+DCY*(TCV+THC)*HCL/2.
Z=PI+DIHM+NHM*NTHM+LHM/2.
CM(1)=(X+Y+Z)+5.00
X=PI+LI+DOH++2. -DIH++2. )*NTH+LHH/2.
CM(2)=(X+Y)+5.00
Y=PI+DPM+TRM+NTRM+LRM/2.
CM(3)=(X+Y)*5.00
X=PI4+(DR+RWT)+2. *TRH+NR

FLOW AREA IN PREHEATER

RAFPH=WAPH+TAPH+NAPH

HEAT TRANSFER CONSTANTS

RA1=RAF1
CZ=CPPG+RA1
DEO=2. *WAPH+TAPH/(WAPH+TAPH)
UXY=LAPH+WAPH+2. *NAPH/(NO+CZ)
DT2=LHH+1000 /CZ
CY=CPA+RAF+4. /CMAPH
UX=X*LAPH+WAPH+2. *NAPH/(NO+RAP+CPA)
CY=CYZ+4. /CMAPH
FUEL=0

MINIMUM FLOW AREA FOR FLUE GAS THROUGH GAS HEATER

AF=DOH+LHH+NTH/2.

HEAT TRANSFER AREA GAS HEATER FOR ONE CYLINDER

AH=PI+DOH+LHH+NTH

HEAT CAPACITY OF GAS HEATER FOR ONE CYLINDER

CMH=4. 71*PI4+DOH++2. -DIH++2. +LHH/2

INIALIZATIONS

DE%=0
TH=1
T=0

HEATER MANIFOLD DEAD VOLUME: VHM

VHM=PI4+DIHM+2*LHM+NTHM

HOT DEAD VOLUME PER CYLINDER: VHD

VHD=PI4+DIHM+2*LHM+NTH

REGENERATOR MANIFOLD DEAD VOLUME: VPM

VPM=PI4+DPM+2*LPM+NTRM

REGENERATOR DEAD VOLUME AND HEAT CAPACITY PER CYLINDER: VPR+CH:

IF=FF: 168. 171 172
WRITE(5,168)
FORMAT(8,169)
READ(5,170)
FORMAT(8)
GOTO9

VPD=NP+PI4+DIHM+2+LP=PI4+NP+MH+THM+PH
CM=4. 71*NP+PI4+DR++2*LP+MH+PH+TH
CM=NP+DOH++2*LP
FF=CK*VPD+FF
GOTO171

VPD=NP+PI4+DR++2*LP+L-FF
CM=4. 71*NP+PI4+DR++2*LP+FF
CONTINUE
COOLER DEAD VOLUME PER CYLINDER
ISOOTHERMAL
VCD=VCDO+1-FCR0+PI4+DIC++2+LC+NTC
ADIABATIC
VCD=VCDO+FCR
TOTAL DEAD VOLUME
VTD=VHH+VHD+VRM+VRD+VCD
INTERMEDIATE VALUES TO MAKE ENGINE VOLUMES CALCULATE FASTER
CA=LCR+2
KB=LCR+PC
ACV=PI4+DCY++2
PCV=PI4+(VCY++2+DCP++2)
PCD+PI1+PC
CCV=ACV-PCY
SET INITIAL SPEED, ANGLE, DISTANCE
ERPAD=0
FAPAD=0
DIST=0
OMFG=0
CALCULATE AIR RESISTANCE CONSTANT
VAPAD=1-4+AMAD
SET INITIAL ENGINE VOLUMES
XB=SOFT(VC-PC+COSVAPAD++2)-PC+COSVAPAD-XB
X2=SOFT(VC-PC+COSVAPAD+PI2++2)-PC+COSVAPAD+PI2-XB
X3=SOFT(VC-PC+COSVAPAD+PI2++2)-PC+COSVAPAD+PI2-XB
X4=SOFT(VC-PC+COSVAPAD+PI2++2)-PC+COSVAPAD+PI2-XB
VHA=1.1-5ACV+PC2X1)+VHDW
VCA=1.1-5BCV+X2+VCDW
VHA=1.1-5ACV+PC2X2)+VHDW
VCA=1.1-5BCV+X2+VCDW
VHA=1.1-5ACV+PC2X3)+VHDW
VCA=1.1-5BCV+X3+VCDW
VHA=1.1-5ACV+PC2X4)+VHDW
VCA=1.1-5BCV+X4+VCDW
DO 174 I=1,4
174 VT=1.1-5VTD+VHA=1.1+VCA(I,1)
WORKING GAS PROPERTIES
CP=14.52
CV=10.79
MW=2.02
GOTO179
177 CP=5.2
CV=3.12
MW=4.0
GOTO179
173 CP=1.029
CV=0.7426
MW=29.0
CONTINUE
GAS QUANTITIES
EV=EP-EV
IV=EP+IV
GA=1+1-IV
FP=1.1
VC=P+NW
TVM=0
IG=0
766: C THERMAL CONDUCTANCE BETWEEN APH METAL NODES
767: KAPH=KM*TMAPH*WAPH*NAPH*2.*NO/LAPH
768: C THERMAL CONDUCTANCE BETWEEN ENGINE METAL NODES
769: KME(1)=KM*PI*DCY*(TCY+THC)/HCL
770: KME(2)=KM*PI*DIHM*WTHM*NTHM/LHM
771: KME(3)=KM*PI4*(DOH**2-DIH**2)*NTH/LHH
772: KME(4)=KM*PI*DIRM*WTRM*NTRM/LRM
773: KME(5)=KM*PI*DR*RWT*NR/(LR/2.)+KMX*PI4*DR**2*NR/(LR/2.)
774: KME(6)=KME(5)
775: C WRITE TRANSFER FILE TO DISK
776: 8004 FORMAT(5(F9.3,))
777: WRITE(10,8004) THMG, TPB, TWI, FWI, DM1
778: WRITE(10,8004) TI, DT, ME, RGE1, KAPH
779: WRITE(10,8004) NTHM, DIHM, FFF, THU, LHM
780: WRITE(10,8004) TCR, TID, TAC, TOTT, SPM
781: WRITE(10,8004) RC, LCR, DCY, DDR, DIH
782: WRITE(10,8004) WTHM, NTH, VHD, NR, DR
783: WRITE(10,8004) LR, FF, NS, MSH, THW
784: WRITE(10,8004) VCDX, FCA, DIC, LC, NTC
785: WRITE(10,8004) MIV, NTRM, DIRM, AFR, LRM
786: WRITE(10,8004) DOH, LHM, TMAPH, LAPH, WAPH
787: WRITE(10,8004) TAPH, NAPH, PRL, PRH, WTRM
788: WRITE(10,8004) TST, MIR, RAF, NO, LHV
789: WRITE(10,8004) CMAPH, AFAPH, RA1, CZ, DEQ
790: WRITE(10,8004) UX, DT2, CY, UX, CYY
791: WRITE(10,8004) FUEL, AMF, AH, CMH, DEX
792: WRITE(10,8004) KAR, TIM, VHD, VRD, CMX
793: WRITE(10,8004) VCD, VCA, VTD, XA, XB
794: WRITE(10,8004) HCY, BCY, PI32, RC2, LCY
795: WRITE(10,8004) EARAD, EADEG, DIST, OMEG, GCT
796: WRITE(10,8004) VHA(1,1), VHA(1,2), VHA(1,3), VHA(1,4), VCA(1,1)
797: WRITE(10,8004) VCA(1,2), VCA(1,3), VCA(1,4), VT(1,1), VT(1,2)
798: WRITE(10,8004) VT(1,3), VT(1,4), CP, CV, MW
799: WRITE(10,8004) RX, KK, GA, KR, XC
800: WRITE(10,8004) TQV, IG1, VHM, VRM, RGE2
801: WRITE(10,8004) RGE3, VSP2, VSP3, THH, TRH
802: WRITE(10,8004) RWT, TCY, THC, G, HCL
803: WRITE(10,8004) KM, KMX, THCH, Q1, Q2
804: WRITE(10,8004) EIN, KME(1), KME(2), KME(3)
805: WRITE(10,8004) KME(4), KME(5), KME(6), CM(1), CM(2)
806: WRITE(10,8004) CM(3), CM(4), CM(5), PBIS, PBVS
807: WRITE(10,8004) TREP
808: 5000 STOP
809: END
810:
***** START OF PROGRAM *****
DIMENSION XI(4), IPV(2,4), IV(2,4)
1 F(4), P(4), 4, M(4), FP(4), T0(4), VHA(2,4), VCA(2,4)
2 VT(4), (2,4)
3 P1(4), CM(4), T0A(2,4)
4 OH(4), T1(4), T1K(10), T0X(8), T0C(10), T0C(4), EY(8), KME(3)
5 OH(8), THA(3,4)
6 CMV(3)
7 DIMENSION TM(6,4), XW(2,8,4), CVG(8,4)
8 REAL LOP(L, L), MSH(N, M, M, L, L), LAC, M, KAR, MG1
9 REAL LHH, LHH, FRG, LFRG, MIP, MIP, MIPI, LHH, MIV, LMM, M, M, M
10 REAL NPM, NTH, NTH, NTH, NFH, NFH, KPM, KPM, KME, KME
11 DATA CONSTANTS
12 DATA P14, P1, P12, P12, P12, P12, P12, P12, P12, P12, P12
14 ****** READ TRANSFER FILE FROM DISK ******
15 FORMAT(4150)
16 READ (10, 5004) THM, TRB, TWI, FWH, OM1
17 READ (10, 5004) IT, MSF, FPEL, PAP
18 READ (10, 5004) NTHM, DIHM, FF, THI, LHH
19 READ (10, 5004) TVP, TID, TAC, T0T, SFM
20 READ (10, 5004) LCP, LCP, DCY, DCP, DTH
21 READ (10, 5004) NTHM, NHM, NHM, NR, DR
22 READ (10, 5004) LC, FF, NS, MSH, THW
23 READ (10, 5004) VCD, VCD, VTD, XR, BPC
24 READ (10, 5004) VHR, NHM, NTHM, DIHM, NTPR, DFM, LPM
25 READ (10, 5004) VCD, VCD, VTD, XR, A3, DEO
26 READ (10, 5004) TST, MIP, PAF, NO, LHH
27 READ (10, 5004) CMAP, AFAP, PAIL, OZ, DEO
28 READ (10, 5004) GY, DT2, CV, UXX, CVV
29 READ (10, 5004) FUEL, RHF, AMF, AH, CMH, HMX
30 READ (10, 5004) TAP, TM, VHD, VRD, CMX
31 READ (10, 5004) VCD, VCD, AX, XA, XB
32 READ (10, 5004) VCD, BSY, BP3, BCP, PC2, CVV
33 READ (10, 5004) VCD, VCD, DIST, OMEG, CTC
34 READ (10, 5004) VHA(1,1), VHA(1,2), VHA(1,3), VHA(1,4), VCA(1,1)
READ (10, 8004) VCA(1, 2), VCA(1, 3), VCA(1, 4), VT(1, 1), VT(1, 2)
READ (10, 8004) VT(1, 3), VT(1, 4), CP, CV, MW
READ (10, 8004) RX, KK, QA, KR, XC
READ (10, 8004) TQV, IQ1, QHM, VRM, RGE2
READ (10, 8004) RGE3, YSP2, YSP3, THH, TRH
READ (10, 8004) RN, RC, TC, THC, O, HCL
READ (10, 8004) KM, KMX, THCH, Q1, Q2
READ (10, 8004) Q3, CIN, KME(1), KME(2), KME(3)
READ (10, 8004) KME(4), KME(5), KME(6), CM(1), CM(2)
READ (10, 8004) CM(3), CM(4), CM(5), PBIS, PBVS
READ (10, 8004) TREP
FILE READ
READ (10, 8004) KM, KMX, THCH, Q1, Q2
READ (10, 8004) Q3, CIN, KME(1), KME(2), KME(3)
READ (10, 8004) KME(4), KME(5), KME(6), CM(1), CM(2)
READ (10, 8004) CM(3), CM(4), CM(5), PBIS, PBVS
READ (10, 8004) TREP
FILE READ
C**************************
C ORGANIZE TIMES FOR OPERATING CYCLE
TT = 0.
TI1 = THU + TCR
TI2 = TI1 + TID
TI3 = TI2 + TAC
C BURNER INITIALIZATION
N = NO
NO2 = N/2
DO 200 I = 1, N
TOU(I) = T1
TIN(I) = T1
EY(I) = T1
200 EX(I) = T1
TIN(N+1) = T1
TA = T1
TD = THMG - TWI
FLAME = T1
TOU(N+1) = T1
CFL = 1000.
CFH = 0.
CFH = 0
C INITIALIZE CUMULATIVE HEAT INPUT AND METAL TEMPS
DO 198 I = 1, 4
TM(1, I) = T1
TM(2, I) = T1
TM(3, I) = T1
TM(4, I) = T1
TM(5, I) = (TWI + T1)/2.
TM(6, I) = TWI
M(I) = 0.0
198 QHI(I) = 0.
C SET PRINTOUT OPTION
J = 02
C INITIALIZE VEHICLE INERTIA
VIN = 0.0
C INITIALIZE ENGINE AND VEHICLE SPEED
OMEG = 0.0
SPV1 = 0.0
SPVD = 0.0
108: C INITIALIZE WORKING TIME STEP
109: DDT=DT
110: C INITIALIZE TORQUES
111: TQS=0.0
112: TQV=0.0
113: TNET=0.0
114: C INITIALIZE ENGINE ANGLES
115: EERAD=0.0
116: REV=0.0
117: NER=0
118: NGC=-1
119: MIR=0.
120: RGE=0.
121: C INITIALIZE ENGINE PRESSURE
122: DO 950 J=1,4
123: 950 P1(I)=PRL
124: C INITIALIZE FLAG TO CALCULATE CONDITIONS AT CRANKING
125: I02=0
126: C INITIALIZE OUTPUT FLAGS
127: I0F=0.0
128: GDP=0.0
129: GDI=TOTT/1.,24.
130: C******** DRAW GRAPHIC FRAME IF OPTION IS ON
131: C GRAPHIC FRAME
132: IF(QI-E.00)158,157,158
133: C DRAW OUTLINE
134: 157 CALL CLEAR
135: I1=0
136: J1=0
137: I2=1023
138: J2=0
139: CALL VECTOR(I1,J1,I2,J2)
140: I1=1023
141: J1=779
142: CALL VECTOR(I2,J2,I1,J1)
143: I2=0
144: J2=779
145: CALL VECTOR(I1,J1,I2,J2)
146: I1=0
147: J1=0
148: CALL VECTOR(I2,J2,I1,J1)
149: I1=700
150: J1=0
151: I2=700
152: J2=779
153: CALL VECTOR(I1,J1,I2,J2)
154: C DIVIDE INTO 4 LAYERS LEFT SIDE
155: I1=0
156: J1=629
157: I2=700
158: J2=629
159: CALL VECTOR(I1,J1,I2,J2)
160: I1=479
161: J1=479
162: CALL VECTOR(I1,J1,I2,J2)
C DIVIDE INTO FOUR LAYERS, RIGHT SIDE

I1=700
J1=190
I2=1023
J2=190
CALL VECTOR(I1, J1, I2, J2)
J1=380
J2=380
CALL VECTOR(I1, J1, I2, J2)
J1=570
J2=570
CALL VECTOR(I1, J1, I2, J2)

C DRAW SCHEDULED VEHICLE SPEED
I1=0
J1=632
I2=THU/TOTT*700
J2=632
CALL VECTOR(I1, J1, I2, J2)
I1=THU/TOTT*700
J1=776
CALL VECTOR(I2, J2, I1, J1)
I2=700
J2=776
CALL VECTOR(I1, J1, I2, J2)

C DRAW SCHEDULED ENGINE SPEED
I1=0
J1=482
I2=THU/TOTT*700
J2=482
CALL VECTOR(I1, J1, I2, J2)
I1=THU/TOTT*700
J1=554
I2=THU/TOTT*700
J2=554
CALL VECTOR(I1, J1, I2, J2)

C DRAW HOT METAL GOAL TICK (THMG)
I1=0
J1=200
I2=10
J2=200
CALL VECTOR(I1, J1, I2, J2)

C DRAW COOLING WATER TEMP TICK (TWI)
J1=10
J2=10
CALL VECTOR(I1, J1, I2, J2)

C CALCULATE DISPLAY PARAMETERS
PDIF=PRH
XLOW=SVD+VHD+VCDA
XD=(ACY+BCY)*RC2
CONTINUE
C*****WRITE UNIFIED PRINTOUT--RETURN POINT FOR MAIN LOOP

401 IF(Q3-1.0)390,402,390
402 IF(TIM-POF)390,391,391
391 POF=POF+TREP
WRITE(J,8025)TIM,CFF,REV,DMEO,SPV1,SPVD,DDT
8025 FORMAT(6F8.2,2F8.5,2F8.2)
WRITE(J,8022)TIN(1),TIN(2),TIN(3),TIN(4),TIN(5),TIN(6),TIN(7),
TIN(8),TIN(9)
WRITE(J,8022)EX(1),EX(2),EX(3),EX(4),EX(5),EX(6),EX(7),
EX(8),FLAME
WRITE(J,8022)TOU(1),TOU(2),TOU(3),TOU(4),TOU(5),TOU(6),TOU(7),
TOU(8),TOU(9)
DO 10 I=1,4
10 WRITE(J,8022)TM(1,I),TM(2,I),TM(3,I),TM(4,I),TM(5,I),TM(6,I),TM(7,I),
TM(8,I)
8022 FORMAT(9(F8.2))
WRITE(J,8022)TNET,TDV,TIN,VIN,MIR,MIR,ROE
C*****DISPLAY GRAPHIC DATA, PART 1
390 IF(Q1-1.)20,21,20
21 IF(TIM-GDF)20,393,393
393 GDF=GDF+ODI
C SHOW FUEL FLOW RATE
I1=TIM/TOTT*700
J1=CFF/FFF*777
CALL POINT(I1,J1)
C SHOW AVERAGE HEATER TEMP.
J1=(TA-TWI)/TD*190+10
CALL POINT(I1,J1)
C SHOW FLUE GAS TEMP. ENTERING PREHEATER
J1=(TOU(N+1)-TWI)/TD*190+10
CALL POINT(I1,J1)
C SHOW FLUE GAS TEMP. LEAVING PREHEATER
J1=(TOU(1)-TWI)/TD*190+10
CALL POINT(I1,J1)
C SHOW AVE. HOT METAL SPACE TEMP. (NODE #1)
X=0
DO 145 I=1,4
145 X=TM(1,I)+X
X=X/4.
J1=(X-TWI)/TD*190+10
CALL POINT(I1,J1)
C SHOW AVE METAL TEMP. HOT END REGEN. (NODE #4)
X=0
DO 146 I=1,4
146 X=TM(4,I)+X
X=X/4.
J1=(X-TW1)/TD*190+10
CALL POINT(I1,J1)
C SHOW AVE. METAL TEMP. MIDDLE REGEN. (NODE #5)
X=0
DO 147 I=1,4
147 X=TM(5,I)+X
X=X/4.
J1=(X-TWI)/TD*190+10
CALL POINT(I1,J1)
IF(TIM-THU)20,20,954
C SHOW ENGINE SPEED
J1=OMEG/OM1*72+482
CALL POINT(I1,J1)
IF(TIM-T12)20,20,953
C SHOW VEHICLE SPEED
J1=SPV1/SPM*144+632
CALL POINT(I1,J1)
20 CONTINUE
C*****DISPLAY GRAPHIC DATA, PART 2
C PLOTTING FOR EVERY TIME STEP OF 4 P-V DIAGRAMS
C CHECK TO SEE IF OPTION IS ON
IF(01-1.)852,853,852
853 IF(TIM-THU)85?,852,854
854 DO 985 I=1,4
IPV(2,I)=(CVM(8,I)-XLOW)*323/XDV+700
JPV(2,I)=P1(I)*190/PDIF+190*(4-I)
CALL VECTOR(IPV(1,I),JPV(1,I),IPV(2,I),JPV(2,I))
IPV(1,1)=IPV(2,I)
JPV(1,1)=JPV(2,I)
985 CONTINUE
852 CONTINUE
C*****ENGINE AND VEHICLE CONTROL SUBPROGRAM PART 1
C CHECK TO SEE IF HEAT UP TIME IS EXCEEDED
IF(TIM-THU)503,502,502
503 I01=0
501 GOTO 501
C FIRST TIME CALCULATION OF GAS MASSES AND INITIALIZE PRESSURES
C AND SET GAS TEMPS. TO CURRENT METAL NODE TEMPS.
502 IF(I02-1)504,506,506
504 I02=1
506 C REDUCE TIME STEP AT START OF CRANKING
DDT=DDT/10.
X=PRL*MW/R
DO 980 I=1,4
W(1,1,1)=X*VHA(1,1)/TM(1,1)
W(1,2,1)=X*VHM*2./(TM(1,1)+TM(2,1))
W(1,3,1)=X*VHD*2./(TM(3,1)+TM(2,1))
W(1,4,1)=X*VRM*2./(TM(4,1)+TM(3,1))
W(1,5,1)=X*VRD/(TM(5,1)+TM(4,1))
W(1,6,1)=X*VRD/(TM(6,1)+TM(5,1))
W(1,7,1)=X*VCD/TWI
W(1,8,1)=X*VCA(1,1)/TWI
980 M(I)=0.
DO 980 K=1,8
980 M(I)=M(I)+W(1,K,1)
C TOTAL GAS MASSES
M(I)=0.
DO 980 K=1,8
980 M(I)=M(I)+W(1,K,1)
C PRESSURES
P1(I)=PRL
C INITIAL PRESSURE PLOT PARAMETERS
JPV(1,I)=(P1(I)-PRL)*195/PDIF+195*(4-I)
C AVERAGE GAS AND METAL TEMPERATURES
TGA(1,1,1)=TM(1,1)
DO 981 K=2,6
TMA(K,1)=(TM(K-1,1)+TM(K,1))/2.
981 TGA(1,K,1)=TMA(K,1)
TMA(7,1)=TWI
TMA(8,1)=TWI
TMA(1,7,1)=TWI
TMA(1,8,1)=TWI
93
C CUMULATIVE GAS VOLUMES
331
332
333
334
335
336
337
338
339
C VOLUME PLOT PARAMETERS
340
341
342
343
344
345
346
347
348
C TEST TO SEE IF ENGINE SHOULD BE CRANKED
349
350
351
352
353
354
355
356
357
C CALCULATE ANGLE INCREMENT
358
359
360
361
362
363
364
365
366
367
C INDEX ENGINE ANGLE MEASURES
368
369
370
371
372
C ERRASE PV PLOT FIELD AFTER EVERY 5 REVOLUTIONS
373
374
375
C CHECK TO SEE IF ENGINE SHOULD BE IDLEING OR IN GEAR
376
377
378
C ADJUST ENGINE PRESSURES TO CONTROL SPEED WHILE ENGINE IS IDLEING
379
380
381
382
383
384
385
386
387
388
389
C COMPUTE NEW ANGULAR VELOCITY
OMEG=DANG/DDT
GOTO 501
C ENGINE AND VEHICLE CONTROL WHILE ENGINE IS IN GEAR
I6=2
C GEAR CHANGE TIME APPLIED TO ALL GEARS
IF(NGC)170,171,172
170 IF(TIM-(TI2+GCT))900,901,901
RGE=(TIM-TI2)+RGE1/GCT
GOTO 910
900 RGE=RGE1
GOTO 910
906 NGC=0
TIMX=TIM
GOTO 910
904 IF(TIM-(TI2+GCT))906,905,905
901 RGE=RGE1
GOTO 910
906 NGC=0
TIMX=TIM
GOTO 910
171 IF(TIM-(TIMX+GCT))162,163
162 RGE=RGE1+(TIM-TIMX)+(RGE2-RGE1)/GCT
GOTO 910
163 CONTINUE
IF((SPV1-VSP2)907,908,908
RGE=RGE2
TIMX=TIM
GOTO 910
172 IF(TIM-(TIMX+GCT))164
164 RGE=RGE2+(RGE2-RGE1)*(TIM-TIMX)/GCT
GOTO 910
167 RGE=RGE3
GOTO 910
171 IF(TIM-(TIMX+GCT))162,163
162 RGE=RGE1+(TIM-TIMX)+(RGE2-RGE1)/GCT
GOTO 910
163 CONTINUE
IF((SPV1-VSP2)907,908,908
RGE=RGE2
TIMX=TIM
GOTO 910
172 IF(TIM-(TIMX+GCT))164
164 RGE=RGE2+(RGE2-RGE1)*(TIM-TIMX)/GCT
GOTO 910
167 RGE=RGE3
GOTO 910
C ADDITIONAL EFFECTIVE ENGINE INERTIA DUE TO VEHICLE ATTACHMENT
VIN=MIV*(RGE^2/2.*PI**2)
C FIND SCHEDULED VEHICLE SPEED
IF(TIM-TI7)912,911,911
912 SPUD=SPM*(TIM-TI7)^TAC
GOTO 917
911 SPVD=SPM
C ADJUST ENGINE PRESSURE TO CONTROL VEHICLE SPEED
917 IF(SPV1-SPVD)909,940,940
909 MIP1=MIR
942 MIP1=MIP
GOTO 943
941 MIP1=MIR*(SPV1-SPVD)/PBVS
943 X=PRL
GOTO 955
939 IF((SPV1-SPVD-PBVS))931,931,932
938 MIP1=MIR
GOTO 933
932 MIP1=MIR*(SPV1-SPVD)/PBVS
933 X=PPL
955 CALL MASS(IG7, PX, MIP1, DDT, X, P1, EADEG)
C TORQUE DUE TO VEHICLE ROLLING FRICTION: AIR FRICTION
PF=MIV*0.0015+0.000691*SPV1+0.0000195*SPV1**2
AF=KAR+SPV1**2
TOV=(RF+AF)*RGE/2.*PI
C COMPUTE NEW ANGULAR VELOCITY
OMEG=DANG/DDT
C COMPUTE NEW VEHICLE SPEED
SPV1=OMEG*RGE/2.*PI
C ONE LINE CHECK DISPLAY TO SCREEN
501 WRITE(5,8030)TIME,CFF,REV,OMEG,SPV1,SPVD,RE,NCC
502FORMAT(7ER3.13)
C INDEX TIME
513TIME=TIME+DOT
C*******END ENGINE AND VEHICLE CONTROL SUBPROGRAM PART 1
C *****FURNER AND HEAT CONDUCTION SUBPROGRAM
C INDEX APH METAL NODE TEMPERATURES
524DO8050I=1,N
5258050EXCY=EY(I)
C FIND AVERAGE HEATER TEMPERATURE FOR CONTROL PURPOSES
540:TA=(TM(2,1)+TM(3,1)+TM(2,2)+TM(3,2)+TM(2,3)+TM(2,4)
541+TM(2,4))/8.
C TEMPERATURE ERROR (FOR CONTROL)
547TE=THMC-TA
555IF(TE-405,405,406
567405CFF=0.91EFF
563GOTO408
569406IF(TE-TPR408,407,407
579407EFF=EFF
571GOTO408
577408EFF=EFF+TEM. TPR
577409CONTINUE
571FUEL=FUEL+EFF*DOT
C CHANGE HEAT TRANSFER FACTORS IF CFF HAS CHANGED SIGNIFICANTLY
577IF(CFF-CFF)-404,420,420
577404IF(CFF-CFF)-420,420,403
C HEAT TRANSFER FACTOR, AIR SIDE
579405GRAPH=CFF-RAP/RA
587RE=DE0+GRAPH+2500
593CALC STAN=P(RE,STN)
599Y=U=STN+GRAPH+1.19/CFF
599IF(Y GT 72)XX=72
591XX=EXP(X)
C HEAT TRANSFER FACTOR, FLUE GAS SIDE
585GRAPH=CFF-PA1/AG
587RE=DE0+GRAPH+2500
593CALC STAN=P(RE,STN)
599Y=STN+GRAPH+1.19/CFF
599IF(Y GT 72)XX=72
591XX=EXP(X)
C HEAT TRANSFER FACTOR, GAS HEATER
597UH=(DOH*CFF-PAL*AMF/ 0006)*C0.592+0.0022/DOH
597V=4+UH+H/CFF+C7)
595IF(V GT 72)XX=72
591XX=EXP(X)
C RESET FLOW BOUNDS
599CFF=1.C*EFF
599CFL=0.9*EFF
C CALCULATE APH AIR TEMPERATURES
601DO420I=1,N
602420TIN(I+1)=EXP((EX(I)-TIN(I))/XY
C FIND FLAME TEMPERATURE
502FLAME=TIN+N+1)+DT2
C DETERMINE OUTLET FLUE GAS TEMP. FROM HEATERS

DO 437 I=1, N
X=(TM(2, I)+TM(3, I))/2.
T3A(I)=X+(FLAME-X)/XH

C AVERAGE FLUE GAS TEMPERATURES

TOU(N+1)=(T3A(1)+T3A(2)+T3A(3)+T3A(4))/4.

C EXIT FLUE GAS TEMPERATURES THROUGH AIR PREHEATER

DO446 I=1, N
K=N-I+1
TOU(K)=EX(K)+(TOU(K+1)-EX(K))/XZ

C CHANGE APH METAL NODE TEMP DUE TO CONVECTION AND CONDUCTION

DO 430 I=1, N
X=CFF*RAF*CPA*(TIN(I+1)-TIN(I))+DDT
Y=CFF*RA1*CPFG*(TOU(I+1)-TOU(I))+DDT
IF(I-I)448,448,450

448 I=KAPH*(EX(I+1)-EX(I))*DDT
GOTO 452

449 I=KAPH*(EX(I+1)-2.*EX(I)+EX(I-1))*DDT
GOTO 452

450 I=KAPH*(EX(I)-EX(I-1))*DDT

455 EXIT(I)=EXIT(I)+(2+Y-X)*CMAPH

C CHANGE ENGINE METAL NODE TEMPS. DUE TO CONDUCTION AND OUTSIDE CONVECTION

DO 489 I=1, N
A=K:ME(1)*(TM(1, I)-TW(1))*DDT
B=K:ME(2)*(TM(2, I)-TM(1, I))*DDT
TM1(1, I)=TM(1, I)+(A+B)*CM(1)
A=K:ME(3)*(TM(3, I)-TM(2, I))*DDT
C=(CFF/4,*.RA1*CPFG*(FLAME-T3A(I))*DDT)*2.
TM1(2, I)=TM(2, I)+(C-A-B)*CM(2)
B=K:ME(4)*(TM(4, I)-TM(4, I))*DDT
TM1(3, I)=TM(3, I)+(A+C-B)*CM(2)
A=K:ME(5)*(TM(5, I)-TM(5, I))*DDT
B=K:ME(6)*(TM(6, I)-TM(6, I))*DDT
TM1(5, I)=TM(5, I)+(A-B)*CM(5)

489 TM1(5, I)=TM(5, I)+(A-B)*CM(5)

C INDEX OF TM1(K, I) TO TM(K, I)

DO 422 K=1, 5
DO 426 I=1, 4
TM1(K, I)=TM1(K, I)
CONTINUE

426 CONTINUE

422 CONTINUE

420 CONTINUE

C AVERAGE METAL TEMPERATURES FOR ISOTHERMAL NODES

DO 561 I=1, 4
DO 562 I=1, 6
TM/I=TM(I)+TM(I+1)+TM(I-1)+TM(I-1)
CONTINUE

561 CONTINUE

C VI++++ END OF BURNER AND HEAT CONDUCTION SUBPROGRAM

C VI++++ CONTROL PROGRAM PART 3

C VI++++ TEST FLAG TO DECIDE WHETHER TO GO ON TO NEXT SUBPROGRAM

IF(I61-1)481,425,425

97
**ENGINE TORQUE AND INTERNAL HEAT TRANSFER SUBPROGRAM**

**STEP 1 -- CALCULATE NEW ENGINE VOLUMES**

\[
X_1 = \sqrt{(R - C \cdot \sin(\Theta - \pi / 2))^2 - R \cdot \cos(\Theta - \pi / 2) - X_2}
\]

\[
X_2 = \sqrt{(R - C \cdot \sin(\Theta + \pi / 2))^2 - R \cdot \cos(\Theta + \pi / 2) - X_1}
\]

\[
X_3 = (R - C \cdot \sin(\Theta + \pi / 2))^2 - R \cdot \cos(\Theta + \pi / 2) - X_2
\]

\[
X_4 = \sqrt{(R - C \cdot \sin(\Theta - \pi / 2))^2 - R \cdot \cos(\Theta - \pi / 2) - X_3}
\]

\[
Y_{1,1} = C_{Y1} \cdot X_1 + V_{HD,1}
\]

\[
Y_{1,2} = C_{Y2} \cdot X_2 + V_{HD,2}
\]

\[
Y_{1,3} = C_{Y3} \cdot X_3 + V_{HD,3}
\]

\[
Y_{1,4} = C_{Y4} \cdot X_4 + V_{HD,4}
\]

**CALCULATE NEW ENGINE SPACE CUMUMATIVE VOLUMES**

\[
C_{VM}(1, I) = Y_{1, I}
\]

\[
C_{VM}(2, I) = C_{VM}(1, I) + V_{HD, I}
\]

\[
C_{VM}(3, I) = C_{VM}(2, I) + V_{HD, I}
\]

\[
C_{VM}(4, I) = C_{VM}(3, I) + V_{HD, I}
\]

\[
C_{VM}(5, I) = C_{VM}(4, I) + V_{HD, I}
\]

\[
C_{VM}(6, I) = C_{VM}(5, I) + V_{HD, I}
\]

**CONTINUE**

**STEP 2 -- CHANGE IN GAS VOLUMES, TEMPERATURES AND GAS NODE INVENTORIES**

**OF WORKING SPACE THAT CAN HAVE ITS GAS INVENTORY ADJUSTED.**

**X**

**C**

**VOLUME OF GAS ADDED(+) OR REMOVED(-) AT CURRENT PRESSURE AND TEMP.**

**FOR THAT WORKING SPACE**

\[
Y = (P / I_G)^3 \cdot (P / X)^{2 \cdot \pi / 2}
\]

**C GAS INVENTORY CHANGE**

\[
\text{IF}(X > Y)
\]

**C TEMP. OF ADDED GAS**

\[
Y_{H} = Y_{TH1} \cdot (P / X)^{2 \cdot \pi / 2} + Y_{V}
\]

**C MASS ADDED**

\[
M_2 = P / X \cdot V_{H} \cdot Y_{V} \cdot X_2
\]

**C NEW TEMPERATURES DUE TO INVENTORY CHANGE**

\[
T_{K} = (P / X)^{2 \cdot \pi / 2} + M_2
\]

**C NEW PRESSURE DUE TO INVENTORY CHANGE**

\[
P_{K} = M_2
\]

**C NEW CUM. VOL. AND GAS NODE INVENTORIES DUE TO GAS ADDED OR REMOVED**

\[
\text{IF}(X > Y)
\]

**C GAS ADDED OR NO CHANGE**

\[
K = 1.7
\]

\[
S = (P / X)^{2 \cdot \pi / 2} + M_2
\]

\[
W_{K} = (P / X)^{2 \cdot \pi / 2} + M_2
\]

\[
GOTO 807
\]
C GAS REMOVED
DO 804 K=1,8
CVG(K,IG3)=CVG(K,IG3)*Y
IF(CVG(K,IG3) CVM(8,IG3)) 804,804,806
806 IF(ZZ*103,103,104
W(1,K,IG3)=W(1,K,IG3)*((CVM(8,IG3)-CVG(K-1,IG2))/
1 (CVG(K,IG3)-CVG(K-1,IG2))
ZZ=.Z.
GOTO 105
103 W(1,K,IG3)=0.
105 CVG(K,IG3)=CVM(8,IG3)
804 CONTINUE
C RE-ADD MASSES
DO 807 M(IG3)=0.
DO 118 K=1,8
M(IG3)=M(IG3)+W(1,K,IG3)
118 CONTINUE
C STEP 3--DETERMINE PRESSURE, TEMPERATURE AND VOLUME CHANGES OF ORIGINAL
C VOLUMES DUE TO TOTAL VOLUME CHANGE ASSUMING NO HEAT TRANSFER
DO290 I=1,4
C TOTAL VOLUME RATIO
X(I)=CVG(I,IG3)/CVM(I,IG3)
C NEW GAS TEMPERATURES
XT(I)=X(I)**(1/KK-1)
DO 951 K=1,8
TGA(I,K,I)=TGA(I,K,I)*XT(I)
951 CONTINUE
C CUMULATIVE VOLUMES OF GAS NODES AFTER TOTAL VOLUME CHANGE
DO 983 K=1,8
CVG(K,IG3)=CVG(K,IG3)*X(I)
983 CONTINUE
C STEP 4--COMPUTATION OF TEMPERATURE AND MASS FLOW IN EACH
C ENGINE SPACE DUE TO GAS FLOW BUT NO HEAT TRANSFER
C THIS VERSION ALLOWS UNLIMITED MASS FLOW DURING ONE TIME STEP
C CALCULATE FOR INC WORKING SPACES
DO 290 I=1,4
C LET K=SOLID INDEX AND L=GAS INDEX
K=1
L=1
C ZERO OUT MASS ARRAY AFTER MASS FLOW
DO 349 II=1,8
TGA(2,II,I)=0
349 W(2,II,I)=0
C SET SECOND TIME FLAG
II=1
C RETURN POINT OF DECISION TREE
348 IF(CVG(L,IG3)-CVM(K,IG3)) 345,346,347
C**** CUM GAS VOL. LESS THAN CUM. METAL VOLUME
345 IF(II) 354,354,355
354 II=1
W(2,K,I)=RM
TGA(2,K,I)=TGA(1,L,I)
GOTO358
355 Y=W(2,K,I)
W(2,K,I)=W(2,K,I)+W(1,L,I)
TGA(2,K,I)=(TGA(2,K,I)*Y+TGA(1,L,I)*W(1,L,I)-W(2,K,I)
358 CONTINUE
C INDEX GAS NODE Flag AND RETURN

L=L+1
C CHECK FOR END OF MASS FLOW CALCULATION
IF(L.GE.9) GOTO 310
C RETURN
GOTO 248

C CHECK FIRST TIME Flag
IF(I)810.810.850
C ADDITION OF METAL NODE LEADS TO EQUAL VOLUMES
W(2,K,I)=PM
TGA(2,K,I)=TGA(1,L,I)
GOTO 851
C ADDITION OF GAS NODE LEADS TO EQUAL VOLUMES
C FIND MASS TO COMPLETE METAL NODE SPACE
550 Y=W(2,K,I)
W(2,K,I)=W(2,K,I)+W(1,L,I)
C FIND AVERAGE TEMP. OF GAS NOW IN METAL NODE SPACE
TGA(2,K,I)=(TGA(2,K,I)*Y+TGA(1,L,I)*W(1,L,I))/W(2,K,I)
C SET FIRST Flag
II=1
C INDEX SOLID AND GAS NODE Flags
L=L+1
K-K+1
C CHECK FOR END OF MASS FLOW CALCULATION
IF(K.GE.9 OR L.GE.9) GOTO 310
C RETURN
GOTO 248
C CHECK FIRST TIME Flag
IF(I)347.343.344
C FIRST TIME FOR NEW GAS NODE
344 PP=(CVM(K,I)-CVG(L-1,I))/<CVG(L,I)-CVG(L-1,I)>
PM=(1-PP)*W(1,L,I)
X=PP*W(1,L,I)
Y=W(2,K,I)
W(2,K,I)=W(2,K,I)+X
TGA(2,K,I)=(TGA(2,K,I)*Y+TGA(1,L,I)*X)/W(2,K,I)
GOTO 253
C AFTER THE FIRST TIME
342 PP=(CVM(K,I)-CVM(K-1,I))/<CVG(L,I)-CVM(K-1,I)>
W(2,K,I)=PM*PP
PM=PM-W(2,K,I)
TGA(2,K,I)=TGA(1,L,I)
C RESET FIRST Flag ON GAS VOLUME SHORT SIDE
II=0
C INDEX SOLID NODE Flag
K=K+1
C CHECK FOR END OF FLOW CALCULATION
IF(K.GE.9) GOTO 310
C RETURN
GOTO 348
C FIND AND SHOW TOTAL MASS AFTER MASS FLOW
DO 326 K=1,8
X=X+X*(2.K, I)
ERRFL=MAX(1, I)
IF(ABS(ERRFL)=1)379,379,329
WRITE(J, 329)ERRFL, I
WRITE(J, 329)FORMAT(/ FLOW ERROR IS'X'E10. 4,' IN WORKING SPACE # I')
DO 326 K=1,8
WRITE(J, 154)(X'-1, K, I), (X'-K, I), CMK, (I), (CMK, I)
1 TGA(I, K, I), TGA(2, K, I)
FORMAT(I, 34F10. 4)
STOP
CONTINUE
CONTINUE
CONTINUE
C STEP 5--CHANGE IN TEMPERATURE OF GAS AND METAL NODES DUE TO
C HEAT TRANSFER WITH NO VOLUME CHANGE
C IN GAS COOLER
DO 690 I=1,4
C HEAT RECEIVED BY METAL NODE 1
QMI(I)=CV*W(2, 2, I)*TGA(2, 2, I)-TMA(2, I)/2
C HEAT RECEIVED BY METAL NODE 2
X=CV*W(2, 3, I)*TGA(2, 3, I)-TMA(2, I)/2
OM(I)=OM(I)+X
C HEAT RECEIVED BY METAL NODE 3
Y=CV*W(2, 4, I)*TGA(2, 4, I)-TMA(4, I)/2
OM(I)=OM(I)+Y
C HEAT RECEIVED BY METAL NODE 4
X=CV*W(2, 5, I)*TGA(2, 5, I)-TMA(5, I)/2
OM(I)=OM(I)+X
C HEAT RECEIVED BY METAL NODE 5
Y=CV*W(2, 6, I)*TGA(2, 6, I)-TMA(6, I)/2
OM(I)=OM(I)+Y
C HEAT RECEIVED BY METAL NODE 6
X=CV*W(2, 7, I)*TGA(2, 7, I)-TMA(7, I)/2
OM(I)=OM(I)+X
C CHANGE IN AVERAGE GAS TEMPERATURES DUE TO HEAT TRANSFER
DO 141 I=1,4
TM(I)=TM(I)+0.5*(TGA(I, 1)-TMA(I))
C CHANGE IN METAL NODE TEMPERATURES DUE TO HEAT TRANSFER
DO 142 K=1,5
TM(K, I)=TM(K, I)+OM(K, I)*CM(K)
CONTINUE
CONTINUE
C STEP 6--NEW PRESSURES FOR EACH SPACE DUE TO HEAT TRANSFER WITH NO
C VOLUME CHANGE
DO 740 I=1,4
C HOT SPACE
P3(I, 1)=W(2, 1, I)*XC*TGA(2, 1, I)*VHM(2, I)
C HEATER MANIFOLD
831 C HEATER
P3(I, 2)=W(2, 2, I)*XC*TGA(2, 2, I)*VHM
C HOT SPACE
P3(I, 2)=W(2, 2, I)*XC*TGA(2, 2, I)*VHD
C REGENERATOR MANIFOLD
P3(1,4) = W(2, 4, I) * TQA(2, 4, I) / VRM

C REGENERATOR HOT HALF
P3(1, 5) = W(2, 5, I) * TQA(2, 5, I) / (VRD / 2)

C REGENERATOR COLD HALF
P3(1, 6) = W(2, 6, I) * TQA(2, 6, I) / (VRD / 2)

C COOLER
P3(1, 7) = W(2, 7, I) * TCA(2, 7, I) / VCD

C COLD SPACE
P3(1, 8) = W(2, 8, I) * TCA(2, 8, I) / VCA(2, I)

C STEP 7 -- ADIABATIC PRESSURE EQUILIBRICATION AT CONSTANT TOTAL VOLUME

C FINAL COMMON PRESSURE FOR INCREMENT
X = VHA(2, I) * P3(1, 1) ** KR
X = X + VHA * P3(1, 2) ** KR
X = X + VHD * P3(1, 3) ** KR
X = X + VRD / 2 * P3(1, 5) ** KR
X = X + VRD / 2 * P3(1, 6) ** KR
X = X + VCD * P3(1, 7) ** KR
X = X + VCA(2, I) * P3(1, 8) ** KR
P4(1) = (X / VT(2, I)) ** KR

C STEP 7A -- GAS NODE TEMPERATURES AFTER ADIABATIC PRESSURE EQUILIBRICATION
DO 133 K = 1, 8
TQA(2, K, I) = TQA(2, K, I) * (P4(I) / P3(I, K)) ** GA

C STEP 7B -- CUMULATIVE VOLUMES OF GAS NODES DUE TO PRESSURE EQUILIBRICATION
DO 134 K = 2, 9
C VOLUMES
VT(1, I) = VT(2, I)
VCA(1, I) = VCA(2, I)
VHA(1, I) = VHA(2, I)

C PRESSURES
P1(I) = P4(I)

C TEMPERATURE
DO 364 K = 1, 8
TQA(1, K, I) = TQA(2, K, I)

C MASSES
DO 750 K = 1, 8
WC 1, K, I ) = WC 2, K, I )
CONTINUE

C STEP 9 -- DETERMINE ENGINE TORQUE AT OUTPUT SHAFT
C INDICATED ENGINE TORQUE, FORCE ON PISTONS, NEWTONS
FP(1) = 100 * (-P4(1) + ACY + P1(4) + BCY - (P1(4) - 0.1) * CCY)
FP(2) = 100 * (-P1(1) + BCY - P1(2) + ACY - (P1(2) - 0.1) * CCY)
FP(3) = 100 * (-P1(2) + BCY - P1(3) + ACY - (P1(3) - 0.1) * CCY)
FP(4) = 100 * (-P1(3) + BCY - P1(4) + ACY - (P1(4) - 0.1) * CCY)

C TORQUE ON EACH CRANK, N-M, CCW IS POSITIVE
TQ(1) = RC / 100 * SIN(EARAD) * FP(1)
TQ(2) = RC / 100 * SIN(EARAD + P1(2)) * FP(2)
TQ(3) = RC / 100 * SIN(EARAD + P1(3)) * FP(3)
TQ(4) = RC / 100 * SIN(EARAD + P1(32)) * FP(4)
C INDICATED TORQUE FOR ENGINE
T01=T0(1)+T0(2)+T0(3)+T0(4)
PAV=(P1(1)+P1(2)+P1(3)+P1(4))/4.

C SHAFT TORQUE FOR ENGINE
SP=QMEG/(2.*PI)
TOS=TOI+ME/100.*(.99862-.0000145*OMEG+2*:*(1.-OMEG+.000491+
1.PAV**(-1.841))

C****END OF ENGINE TORQUE AND INTERNAL H.T. SUBPROGRAM
C*****CONTROLP PROGRAM PART 3
IF(TIN-TOTT)401,795,795
C*****FINAL SUMMARY REPORT
WRITE(J,798)FUEL,TOTT,SPV1
FORMAT( 'FUEL,TOTT,SPV1',3F10.3)
STOP
END

SUBROUTINE MASS(IG3,PX,MIR1,DDT,X,P1,EADEG)
DIMENSION P1(4)
REAL M2,MIR1
IF(EADEG-45.)860,860,890
IF(EADEG-135.)862,862,856
IF(EADEG-225.)864,864,857
IF(EADEG-315.)858,858,860
P =X+(P1(1)-X)*EXP(-MIR1*DDT)
GOTO875

C GAS CHANGE IN WORKING SPACE 1
IG3=1
P =X+(P1(1)-X)*EXP(-MIR1*DDT)
GOTO875

C GAS CHANGE IN WORKING SPACE 4
IG3=4
P =X+(P1(4)-X)*EXP(-MIR1*DDT)
GOTO875

C GAS CHANGE IN WORKING SPACE 3
IG3=3
P =X+(P1(3)-X)*EXP(-MIR1*DDT)
GOTO875

C GAS CHANGE IN WORKING SPACE 2
IG3=2
P =X+(P1(2)-X)*EXP(-MIR1*DDT)
RETURN
END

SUBROUTINE STANTN(RE,STN)
IF(RE-2000)100,100,200
STN=EXP(1.6908-0.3363*ALOG(RE))
GOTO300
STN=EXP(-4.0555-0.1903*ALOG(RE))
RETURN
END
C SUBROUTINE USED TO ERASE PV DISPLAY FIELD

SUBROUTINE ERASE


30 CALL CONOUT(GS)

CALL CONOUT(ES)

CALL CONOUT(DE)

YH=777/32+32

YL=MOD(777, 32)+96

XH=JP/32+32

XL=MOD(JP, 32)+64

CALL CONOUT(YH)

CALL CONOUT(YL)

CALL CONOUT(XH)

CALL CONOUT(XL)

DO 10 I=1, 200

M=I+1

10 CONTINUE

YH=2/32+32

YL=MOD(2, 32)+96

CALL CONOUT(YH)

CALL CONOUT(YL)

CALL CONOUT(XH)

CALL CONOUT(XL)

DO 20 I=1, 200

M=I+1

20 CONTINUE

CALL CONOUT(ES)

CALL CONOUT(AA)

CALL CONOUT(US)

CALL CONOUT(CA)

CALL CONOUT(CA)

CONTINUE

RETURN

END
6.0 PROGRAM USERS MANUAL

This section gives the directions for using the program described in this report. It is sometimes particular to the Altos computer used in the program development but the intent of each instruction is given so that another computer can also be used. Instructions are as follows:

6.1 Load Program CNTLA

A. Turn on computer.
B. Insert disc.
C. Type CNTLA (return)
D. Following message appears on screen
   
   **READ IN**
   **TYPE 1 LEAVE IN BASE CASE**
   **TYPE 2 BRING IN STORED DATA FROM LAST CASE**

When the program starts, the data statements are always read. This initiates the base case. The program has been used before. A file has been created which transfers the input values to program CNTLB. If the operator has already made a lot of changes and wants to make some more, he should type 2 and then key (return). If he is starting or wants to start over with the base case, he should type 1 and (return).

E. Type either 1 or 2 and (return).
F. The following directions appear on the screen:
   
   CNTLA INPUT ADJUSTMENT PROGRAM. TO CHANGE TYPE 2 DIGIT INPUT NUMBER, A SPACE, AND THE NEW INPUT VALUE WITH A DECIMAL POINT.
   TO CONTINUE HIT RETURN.

G. Hit return.

H. A table appears on the screen as shown in Table 6.1. To save space the input parameters are identified by numbers only and the values are given just by a number. Table 6.2 gives the identity of each input parameter. This table is given in numerical order of the input numbers. The symbol used in the program, the meaning, the resident value and the units are given.

Table 6.3 gives the same information organized by subject. If one wants to change a particular operating condition, it would be easier to look up the variable number in Table 6.3. Table 6.2 would be useful if the question is what a particular variable number means or if additional variables are needed to be added.

I. To change a variable type the variable number, a space and then the new variable value with a decimal point in the appropriate place. After pressing (return), the change menu is redisplayed with the new change.

This process may be repeated as many times as desired. When calculation is to proceed, type 99 and (return). The word STOP will show on the screen when the program is finished and the intermediate values have been filed in FORT10.DAT. Also the prompt ->A will appear. The operator is now finished with CNTLA. In fact, he is out of it.
Table 6.1

INPUT PARAMETER TABLE FOR BASE CASE

| OPERATING CONDITIONS BY NUMBER | *
|--------------------------------|*
| 01 922.200 * 02 50.000 * 03 300.000 * 04 1575.000 * 05 40.000 * | *
| 06 300.000 * 07 .500 * 08 90.000 * 09 1 * 10 .540 * | *
| 11 36.000 * 12 .472 * 13 4.850 * 14 20.000 * 15 7.950 * | *
| 16 1.000 * 17 1.000 * 18 30.000 * 19 90.000 * 20 22.400 * | *
| 21 2.325 * 22 13.650 * 23 10.160 * 24 4.060 * 25 .472 * | *
| 26 .004 * 27 36.000 * 28 11.590 * 29 6.000 * 30 3.500 * | *
| 31 2.500 * 32 .200 * 33 0.000 * 34 0.000 * 35 0.000 * | *
| 36 196.920 * 37 .950 * 38 1.115 * 39 12.900 * 40 312.000 * | *
| 41 1100.000 * 42 36.000 * 43 .472 * 44 1.120 * 45 7.950 * | *
| 46 .640 * 47 25.500 * 48 .010 * 49 10.000 * 50 .500 * | *
| 51 .790 * 52 50.000 * 53 5.000 * 54 10.000 * 55 .604 * | *
| 56 1000.000 * 57 150.000 * 58 16.550 * 59 8.000 * 60 46.432 * | *
| 61 1.000 * 62 1.000 * 63 2.000 * 64 4.470 * 65 13.420 * | *
| 66 1.500 * 67 .500 * 68 .418 * 69 1.270 * 70 .381 * | *
| 71 .841 * 72 10.030 * 73 .200 * 74 .817 * 75 .381 * | *
| 76 1.000 * 77 2.000 * 78 1.000 * 79 50.000 * 80 5.000 * | *
| 81 1.000 * 82 5.000 * 83 | *

II XXXXXXXXXX TYPE 99 TO CALCULATE' AND FILE INTERMEDIATE VALUES
### Table 6.2

**CNTLA CHANGE TABLE BY NUMBER**

<table>
<thead>
<tr>
<th>Number</th>
<th>Symbol</th>
<th>Meaning</th>
<th>Resident Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>THMG</td>
<td>Temperature, hot metal, goal</td>
<td>922.2</td>
<td>K</td>
</tr>
<tr>
<td>2</td>
<td>TPB</td>
<td>Temperature, proportional band in hot metal</td>
<td>50.0</td>
<td>K</td>
</tr>
<tr>
<td>3</td>
<td>TWI</td>
<td>Temperature, water, inlet</td>
<td>300.0</td>
<td>K</td>
</tr>
<tr>
<td>4</td>
<td>FWI</td>
<td>Flow of cooling water for entire engine</td>
<td>1575.0</td>
<td>g/sec</td>
</tr>
<tr>
<td>5</td>
<td>OM1</td>
<td>Desired idle speed of engine</td>
<td>40.0</td>
<td>rad/sec</td>
</tr>
<tr>
<td>6</td>
<td>T1</td>
<td>Ambient air temperature</td>
<td>300.0</td>
<td>K</td>
</tr>
<tr>
<td>7</td>
<td>DT</td>
<td>Initial time step</td>
<td>0.5</td>
<td>sec</td>
</tr>
<tr>
<td>8</td>
<td>ME</td>
<td>Mechanical efficiency, engine</td>
<td>90.0</td>
<td>%</td>
</tr>
<tr>
<td>9</td>
<td>Z</td>
<td>Flag for working fluid: 1 for H₂, 2 for He, 3 for air</td>
<td>1</td>
<td>--</td>
</tr>
<tr>
<td>10</td>
<td>RGE1</td>
<td>Vehicle travel per engine revolution in first gear</td>
<td>0.54</td>
<td>meters</td>
</tr>
<tr>
<td>11</td>
<td>NTHM</td>
<td>Number of tubes in heater manifold</td>
<td>36</td>
<td>--</td>
</tr>
<tr>
<td>12</td>
<td>DIHM</td>
<td>Inside diameter of tubes in heater manifold</td>
<td>0.472</td>
<td>cm</td>
</tr>
<tr>
<td>13</td>
<td>FFF</td>
<td>Full fuel flow</td>
<td>4.85</td>
<td>g/sec</td>
</tr>
<tr>
<td>14</td>
<td>THU</td>
<td>Time for engine warm-up, before cranking</td>
<td>20</td>
<td>sec</td>
</tr>
<tr>
<td>15</td>
<td>LHM</td>
<td>Length of tubes in heater manifold</td>
<td>7.95</td>
<td>cm</td>
</tr>
<tr>
<td>16</td>
<td>TCR</td>
<td>Duration of starting motor torque</td>
<td>1.0</td>
<td>sec</td>
</tr>
<tr>
<td>17</td>
<td>TID</td>
<td>Idle time after cranking</td>
<td>1.0</td>
<td>sec</td>
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<tr>
<td>18</td>
<td>TAC</td>
<td>Vehicle acceleration time</td>
<td>30</td>
<td>sec</td>
</tr>
<tr>
<td>19</td>
<td>TOTT</td>
<td>Total simulation time</td>
<td>90</td>
<td>sec</td>
</tr>
<tr>
<td>20</td>
<td>SPM</td>
<td>Cruising speed of vehicle</td>
<td>22.4</td>
<td>m/sec</td>
</tr>
<tr>
<td>21</td>
<td>RC</td>
<td>Radius of engine crank</td>
<td>2.325</td>
<td>cm</td>
</tr>
<tr>
<td>22</td>
<td>LCR</td>
<td>Length of connecting rod</td>
<td>13.65</td>
<td>cm</td>
</tr>
<tr>
<td>23</td>
<td>DCY</td>
<td>Diameter of cylinder</td>
<td>10.16</td>
<td>cm</td>
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<tr>
<td>24</td>
<td>DDR</td>
<td>Diameter of drive rod (at seal)</td>
<td>4.06</td>
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<td>25</td>
<td>DIH</td>
<td>Inside diameter of heater tubes</td>
<td>0.472</td>
<td>cm</td>
</tr>
<tr>
<td>26</td>
<td>WTHM</td>
<td>Wall thickness of tubes in heater manifold</td>
<td>0.084</td>
<td>cm</td>
</tr>
<tr>
<td>27</td>
<td>NTH</td>
<td>Number of heater tubes per cylinder</td>
<td>36</td>
<td>--</td>
</tr>
<tr>
<td>28</td>
<td>VHDX</td>
<td>Extra hot dead volume in end clearance and hot cap clearance per cylinder</td>
<td>11.59</td>
<td>cm³</td>
</tr>
<tr>
<td>29</td>
<td>NR</td>
<td>Number of regenerators per cylinder</td>
<td>6</td>
<td>--</td>
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Table 6.2 (continued)

<table>
<thead>
<tr>
<th>Number</th>
<th>Symbol</th>
<th>Meaning</th>
<th>Resident Value</th>
<th>Units</th>
</tr>
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<tbody>
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<td>30</td>
<td>DR</td>
<td>Diameter of each regenerator</td>
<td>3.5</td>
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<tr>
<td>31</td>
<td>LR</td>
<td>Length of regenerator</td>
<td>2.5</td>
<td>cm</td>
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<tr>
<td>32</td>
<td>FF</td>
<td>Fraction of regenerator volume filled with solid (if zero program calculates FF from dimensions below)</td>
<td>0.2</td>
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</tr>
<tr>
<td>33</td>
<td>NS</td>
<td>Number of screens per regenerator</td>
<td>0.0</td>
<td>--</td>
</tr>
<tr>
<td>34</td>
<td>MSH</td>
<td>Mesh size</td>
<td>0.0</td>
<td>wires/cm</td>
</tr>
<tr>
<td>35</td>
<td>THW</td>
<td>Thickness of wire in screens of regenerator</td>
<td>0.0</td>
<td>cm</td>
</tr>
<tr>
<td>36</td>
<td>VCDX</td>
<td>Cold dead volume not in gas cooler or cold space</td>
<td>196.02</td>
<td>cm$^3$</td>
</tr>
<tr>
<td>37</td>
<td>FCA</td>
<td>Fraction of VCDX that is adiabatic</td>
<td>0.95</td>
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</tr>
<tr>
<td>38</td>
<td>DIC</td>
<td>Diameter of inside of cooler tubes</td>
<td>0.115</td>
<td>cm</td>
</tr>
<tr>
<td>39</td>
<td>LC</td>
<td>Length of cooler tubes</td>
<td>12.9</td>
<td>cm</td>
</tr>
<tr>
<td>40</td>
<td>NTC</td>
<td>Number of cooler tubes per cylinder</td>
<td>312</td>
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<tr>
<td>41</td>
<td>MIV</td>
<td>Mass, inertia of vehicle</td>
<td>1100</td>
<td>Kg</td>
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<tr>
<td>42</td>
<td>NTIRM</td>
<td>Number of tubes in regenerator manifold</td>
<td>36</td>
<td>--</td>
</tr>
<tr>
<td>43</td>
<td>DIRM</td>
<td>Inside diameter of tubes in regenerator manifold</td>
<td>0.472</td>
<td>cm</td>
</tr>
<tr>
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<td>APR</td>
<td>Frontal area of vehicle times shape coefficient</td>
<td>1.12</td>
<td>m$^2$</td>
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<tr>
<td>45</td>
<td>LRM</td>
<td>Length of tubes in regenerator manifold</td>
<td>7.95</td>
<td>cm</td>
</tr>
<tr>
<td>46</td>
<td>DOH</td>
<td>Outside diameter of heater tubes</td>
<td>0.640</td>
<td>cm</td>
</tr>
<tr>
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<td>LHH</td>
<td>Heated length of heater tubes</td>
<td>25.58</td>
<td>cm</td>
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<tr>
<td>48</td>
<td>TMPAH</td>
<td>Thickness of metal separating each flow passage in air preheater</td>
<td>0.01</td>
<td>cm</td>
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<tr>
<td>49</td>
<td>LAPH</td>
<td>Length of air preheater</td>
<td>10.0</td>
<td>cm</td>
</tr>
<tr>
<td>50</td>
<td>WAPH</td>
<td>Width of each air preheater passage</td>
<td>5.0</td>
<td>cm</td>
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<td>TAPH</td>
<td>Thickness of each air preheater flow passage</td>
<td>0.3</td>
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<tr>
<td>52</td>
<td>NAPH</td>
<td>Number of air preheater flow passages in each direction</td>
<td>50</td>
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<tr>
<td>53</td>
<td>PRL</td>
<td>Pressure of working gas in low pressure reservoir</td>
<td>0.5</td>
<td>MPa</td>
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<tr>
<td>54</td>
<td>PRH</td>
<td>Pressure of working gas in high pressure reservoir</td>
<td>10.0</td>
<td>MPa</td>
</tr>
<tr>
<td>55</td>
<td>WMRM</td>
<td>Wall thickness of tubes in regenerator manifold</td>
<td>0.084</td>
<td>cm</td>
</tr>
</tbody>
</table>
Table 6.2 (continued)

<table>
<thead>
<tr>
<th>Number</th>
<th>Symbol</th>
<th>Meaning</th>
<th>Resident Value</th>
<th>Units</th>
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</thead>
<tbody>
<tr>
<td>56</td>
<td>TST</td>
<td>Starting motor torque</td>
<td>1000.</td>
<td>Newton-meters</td>
</tr>
<tr>
<td>57</td>
<td>MIR</td>
<td>Maximum time constant for changing working gas pressure</td>
<td>150.</td>
<td>sec⁻¹</td>
</tr>
<tr>
<td>58</td>
<td>RAF</td>
<td>Mass ratio of air to fuel</td>
<td>16.55</td>
<td>g/g</td>
</tr>
<tr>
<td>59</td>
<td>NO</td>
<td>Number of nodes in air preheater</td>
<td>8</td>
<td>--</td>
</tr>
<tr>
<td>60</td>
<td>LHV</td>
<td>Lower heating value of fuel</td>
<td>46.432</td>
<td>KJ/g</td>
</tr>
<tr>
<td>61</td>
<td>GCT</td>
<td>Gear change time</td>
<td>1.0</td>
<td>sec</td>
</tr>
<tr>
<td>62</td>
<td>RGE2</td>
<td>Vehicle travel per engine revolution in second gear</td>
<td>1.0</td>
<td>meters</td>
</tr>
<tr>
<td>63</td>
<td>RGE3</td>
<td>Vehicle travel per engine revolution in third gear</td>
<td>2.0</td>
<td>meters</td>
</tr>
<tr>
<td>64</td>
<td>VSP2</td>
<td>Vehicle speed to change to second gear</td>
<td>4.47</td>
<td>m/sec</td>
</tr>
<tr>
<td>65</td>
<td>VSP3</td>
<td>Vehicle speed to change to third gear</td>
<td>13.42</td>
<td>m/sec</td>
</tr>
<tr>
<td>66</td>
<td>THH</td>
<td>Thickness of hot cylinder head</td>
<td>1.5</td>
<td>cm</td>
</tr>
<tr>
<td>67</td>
<td>TRH</td>
<td>Thickness of regenerator head</td>
<td>0.5</td>
<td>cm</td>
</tr>
<tr>
<td>68</td>
<td>RWT</td>
<td>Average regenerator wall thickness (for heat conduction)</td>
<td>0.41</td>
<td>cm</td>
</tr>
<tr>
<td>69</td>
<td>TCY</td>
<td>Average engine cylinder wall thickness (for heat conduction)</td>
<td>1.27</td>
<td>cm</td>
</tr>
<tr>
<td>70</td>
<td>THC</td>
<td>Thickness of hot cap cylinder</td>
<td>0.381</td>
<td>cm</td>
</tr>
<tr>
<td>71</td>
<td>G</td>
<td>Gap between hot cap and cylinder wall</td>
<td>0.0406</td>
<td>cm</td>
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<td>72</td>
<td>HCL</td>
<td>Hot cap length</td>
<td>10.03</td>
<td>cm</td>
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<tr>
<td>73</td>
<td>KM</td>
<td>Thermal conductivity of engine walls</td>
<td>0.2</td>
<td>w/cm K</td>
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<tr>
<td>74</td>
<td>KMX</td>
<td>Thermal conductivity of regenerator matrix</td>
<td>0.017</td>
<td>w/cm K</td>
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<tr>
<td>75</td>
<td>THCH</td>
<td>Thickness of hot cap head</td>
<td>0.381</td>
<td>cm</td>
</tr>
<tr>
<td>76</td>
<td>Q1</td>
<td>Graphic option, 1 for yes</td>
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<td>--</td>
</tr>
<tr>
<td>77</td>
<td>Q2</td>
<td>Printout option, 5 to console, 2 to printer</td>
<td>2.0</td>
<td>--</td>
</tr>
<tr>
<td>78</td>
<td>Q3</td>
<td>Periodic report printout option, 1 for yes</td>
<td>1.0</td>
<td>--</td>
</tr>
<tr>
<td>79</td>
<td>EIN</td>
<td>Engine inertia</td>
<td>50</td>
<td>Kg m²</td>
</tr>
<tr>
<td>80</td>
<td>PBIS</td>
<td>Proportional band on engine idle speed</td>
<td>5.0</td>
<td>rad/sec</td>
</tr>
<tr>
<td>81</td>
<td>PBVS</td>
<td>Proportional band on vehicle speed</td>
<td>1.0</td>
<td>m/sec</td>
</tr>
<tr>
<td>82</td>
<td>TREP</td>
<td>Time interval for periodic report printout</td>
<td>5.0</td>
<td>sec</td>
</tr>
</tbody>
</table>
### Table 6.3

**CNTLA CHANGE TABLE ORGANIZED BY SUBJECT**

<table>
<thead>
<tr>
<th>Subject</th>
<th>No.</th>
<th>Symbol</th>
<th>Resident Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Solution output control</strong></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Graphics flag (1 for yes)</td>
<td>76</td>
<td>Q1</td>
<td>1.0</td>
<td>--</td>
</tr>
<tr>
<td>Output flag (2 for printer, 5 for screen)</td>
<td>77</td>
<td>Q2</td>
<td>2.0</td>
<td>--</td>
</tr>
<tr>
<td>Periodic report flag (1 for yes)</td>
<td>78</td>
<td>Q3</td>
<td>1.0</td>
<td>--</td>
</tr>
<tr>
<td>Time interval between printouts</td>
<td>82</td>
<td>TREP</td>
<td>5.0</td>
<td>sec</td>
</tr>
<tr>
<td>Initial time step</td>
<td>7</td>
<td>DT</td>
<td>0.5</td>
<td>sec</td>
</tr>
<tr>
<td>Nodes in air preheater</td>
<td>59</td>
<td>NO</td>
<td>8</td>
<td>--</td>
</tr>
<tr>
<td><strong>Driving Cycle</strong></td>
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<tr>
<td>Warm-up time</td>
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<td>THU</td>
<td>20.</td>
<td>sec</td>
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<tr>
<td>Cranking time</td>
<td>16</td>
<td>TCR</td>
<td>1.0</td>
<td>sec</td>
</tr>
<tr>
<td>Cranking torque</td>
<td>56</td>
<td>TST</td>
<td>1000.</td>
<td>N-m</td>
</tr>
<tr>
<td>Idling time</td>
<td>17</td>
<td>TID</td>
<td>1.0</td>
<td>sec</td>
</tr>
<tr>
<td>Desired idle speed</td>
<td>5</td>
<td>OM1</td>
<td>40.</td>
<td>rad/sec</td>
</tr>
<tr>
<td>Proportional band on idle speed</td>
<td>80</td>
<td>PBIS</td>
<td>5.0</td>
<td>rad/sec</td>
</tr>
<tr>
<td>Acceleration time</td>
<td>18</td>
<td>TAC</td>
<td>30.</td>
<td>sec</td>
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<tr>
<td>Cruising speed</td>
<td>20</td>
<td>SPM</td>
<td>22.4</td>
<td>m/sec</td>
</tr>
<tr>
<td>Total simulation time</td>
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<td>m/sec</td>
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<td>Gear ratio, vehicle travel/revolution</td>
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<tr>
<td>first gear</td>
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<td>m</td>
</tr>
<tr>
<td>second gear</td>
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<td>RGE2</td>
<td>1.0</td>
<td>m</td>
</tr>
<tr>
<td>third gear</td>
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<td>RGE3</td>
<td>2.0</td>
<td>m</td>
</tr>
<tr>
<td>Gear change speeds</td>
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<td>to second gear</td>
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<td>VSP2</td>
<td>4.47</td>
<td>m/sec</td>
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<tr>
<td>to third gear</td>
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<td>VSP3</td>
<td>13.42</td>
<td>m/sec</td>
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<td>sec</td>
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<td>Maximum time constant for changing working gas pressure</td>
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<td>MIR</td>
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<td>sec^-1</td>
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<td><strong>Engine Operating Conditions</strong></td>
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<td>Temperatures</td>
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<td>TPB</td>
<td>50.</td>
<td>K</td>
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<td>water inlet</td>
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<td>TWI</td>
<td>300</td>
<td>K</td>
</tr>
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<td>ambient air</td>
<td>6</td>
<td>T1</td>
<td>300</td>
<td>K</td>
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</table>
Table 6.3 (continued)

<table>
<thead>
<tr>
<th>Subject</th>
<th>No.</th>
<th>Symbol</th>
<th>Resident Value</th>
<th>Units</th>
</tr>
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<td>0.5</td>
<td>MPa</td>
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<td>Z</td>
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<td>46.432</td>
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<td>TCY</td>
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<td>and clearance and hot cap clearance volume</td>
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<tr>
<td>number of tubes per cylinder</td>
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<td>NTHM</td>
<td>36</td>
<td></td>
</tr>
<tr>
<td>inside diameter</td>
<td>12</td>
<td>DIHM</td>
<td>0.472</td>
<td>cm</td>
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<tr>
<td>length</td>
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<td>LHM</td>
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<td>wall thickness</td>
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Table 6.3 (continued)

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<td></td>
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<td>NTH</td>
<td>36</td>
<td>--</td>
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<tr>
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<td>Regenerator manifold</td>
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<td></td>
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<td>number of tubes per cylinder</td>
<td>42</td>
<td>NTRM</td>
<td>36</td>
<td>--</td>
</tr>
<tr>
<td>ID</td>
<td>43</td>
<td>DIRM</td>
<td>0.472</td>
<td>cm</td>
</tr>
<tr>
<td>length</td>
<td>45</td>
<td>LRM</td>
<td>7.95</td>
<td>cm</td>
</tr>
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<td>wall thickness</td>
<td>55</td>
<td>WTRM</td>
<td>0.084</td>
<td>cm</td>
</tr>
<tr>
<td>Regenerator</td>
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<td>thermal conductivity of matrix</td>
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<td>NR</td>
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<td>--</td>
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<td>diameter</td>
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<td>RWT</td>
<td>0.41</td>
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<td>32</td>
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<td>--</td>
</tr>
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<td>number of screens per regenerator</td>
<td>33</td>
<td>NS</td>
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<td>--</td>
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<td>mesh size</td>
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<td>MSH</td>
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<td>thickness of wire in regenerator</td>
<td>35</td>
<td>THW</td>
<td>0.0</td>
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</tr>
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<td>thickness of regenerator head</td>
<td>67</td>
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<tr>
<td>Cooler</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>number of tubes per cylinder</td>
<td>40</td>
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<td>312.</td>
<td>--</td>
</tr>
<tr>
<td>length of tubes</td>
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<td>LC</td>
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<td>38</td>
<td>DIC</td>
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<td>Cooler manifold</td>
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<td>dead volume</td>
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<td>cm³</td>
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<td>fraction adiabatic</td>
<td>37</td>
<td>FCA</td>
<td>0.95</td>
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<td>Drive</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>cylinders per engine</td>
<td>--</td>
<td>--</td>
<td>4</td>
<td>--</td>
</tr>
<tr>
<td>radius of crank</td>
<td>21</td>
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<td>LCR</td>
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<td>cm</td>
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<tr>
<td>engine inertia</td>
<td>79</td>
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<td>50</td>
<td>Kg m²</td>
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<tr>
<td>mechanical efficiency</td>
<td>8</td>
<td>ME</td>
<td>90</td>
<td>%</td>
</tr>
</tbody>
</table>
Besides being able to change any input variable involving engine dimensions and operating conditions, there are some computer solution options that should be discussed here.

**Number 76 - Graphic Flag.** If #76 is 1.0, then CNTLB will go into the graphic parts of the program. If #76 is 0.0, it will not. If the computer does not have graphic capability or the operator does not want to use it, #76 should be 0.0.

**Number 77 - Output Flag.** If #77 is 2.0, then CNTLB will direct its periodic and final output to the printer. If #77 is 5.0, it will be directed to the screen on the console. If #77 is 2.0, be sure the printer is on or the solution will stop with no indication of why.

**Number 78 - Periodic Report Flag.** If #78 is 1.0, a periodic report is printed out or displayed. If in CNTLB #78 is 0.0, then CNTLB will not produce periodic reports.

**Number 82 - Repetition Rate for Periodic Reports.** #82 gives the desired number of seconds between periodic reports. After this desired time is exceeded, the next periodic report will be given. This number is useful in controlling the amount of output from CNTLB to give an adequate but not overwhelming amount.

**Number 7 - Initial Time Step.** #7 gives the time step used in the heat up section of the solution at the start of CNTLB. The program WARM (Appendix A) was used to show that 8 nodes and a time increment of 0.5 second gives adequate accuracy for the solution. #7 can be changed for other time steps. When the engine starts rotating, the program automatically adjusts the time step.

**Number 59 - Nodes in Air Preheater.** Presently the number of nodes in the air preheater is fixed at 8. It cannot be changed in CNTLA. It can in WARM (see Appendix A).

CNTLA produces a data file called FORT10.DAT which is read by CNTLB. The information is transferred by the position in this data file. Therefore, the write statements in CNTLA and the read statements in CNTLB must be identical. Table 6.4 shows the file for the base case.

### 6.2 Load Program CNTLB

A. Type CNTLB (RETURN).

B. Be certain printer is on. (Base case has the intermediate printout go to the printer every 5 seconds of real time.)

C. The message FILE READ appears on the screen. This shows that the data file prepared by CNTLA has been read in.

The solution then proceeds as required by the contract without any operator attention. Pressing the CNTL key and S at the same time will stop the solution or start it again.
Table 6.4

DATA TRANSFER FILE FOR BASE CASE
(Called FORT10.DAT)
(See listing of either CNTLA or CNTLB for identity of numbers)

<p>| | | | | | |</p>
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<td>90.000</td>
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<td>.800</td>
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<td>10.000</td>
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<td>1.000</td>
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</tr>
</tbody>
</table>

5.000
In order to always be in touch with the solution, a line of 8 numbers in exponential format are always read to the console for every time step. Table 6.5 is the heading for this readout.

Periodically, as determined by the program, if the periodic printout option is on, a more complete readout is made either to the console or to the printer. Table 6.6 shows the heading for this output.

The definition of the metallic nodes called out in Table 6.6 is as follows: (See Figure 4.9.)

1. Around hot space
2. Between heater manifold and heater
3. Between heater and regenerator manifold
4. Hot end of regenerator
5. Middle of regenerator
6. Regenerator end of cooler

Figure 3.1 gives the nomenclature for this engine.

If the graphic option is on, the following values are displayed to the screen.

A. Scheduled as a function of time
   1. Engine speed up until start of cranking
   2. Vehicle speed

B. Ticks on left hand border of display to show:
   1. Temperature goal for heater metal
   2. Cooling water temperature

C. Plotted as time progresses versus time
   1. Current fuel flow rate (over full height of display) (Starts out at maximum.)
   2. Temperatures on the scale determined by the two ticks
      a. Flue gas leaving heaters and entering air preheater
      b. Average heater metal temperature
      c. Flue gas leaving air preheater
      d. Average of metal around hot spaces
      e. Average of metal around hot end of regenerators
      f. Average of metal at middle of regenerators
   3. Engine speed on scale determined by specified idle speed
   4. Vehicle speed—compared with desired vehicle speed

D. Pressure-volume work diagrams for the four working spaces. These are on the right side of the screen. Four boxes are drawn. The top box is for working space #1, the second is for working space #2, and so on. Full scale for the pressure is the high pressure gas reservoir. The bottom of each scale is zero pressure.

The temperature plots must be differentiated by comparing the plot with the periodic printout which also contains the same values.

At the end of the program three numbers are displayed. These are:
1. Total fuel consumption, grams
2. Total time, seconds
3. Vehicle speed at end of cycle, m/sec
Table 6.5

HEADING FOR CONSOLE OUTPUT EVERY TIME STEP

<table>
<thead>
<tr>
<th>Cumulative Time, seconds</th>
<th>Current Fuel Flow, g/sec</th>
<th>Engine Revolutions</th>
<th>Engine Speed, rad/sec</th>
<th>Vehicle Speed, meters/sec</th>
<th>Desired Vehicle Speed, meters/sec</th>
<th>Meters Traveled per Engine Revolution</th>
<th>Gear Ratio Flag</th>
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</thead>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-1 1st gear or idling</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>0 2nd gear</td>
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<td></td>
<td></td>
<td>+1 3rd gear</td>
</tr>
<tr>
<td>Cumulative Time, seconds</td>
<td>Current Fuel Flow, g/sec</td>
<td>revolutions</td>
<td>Engine Speed, rad/sec</td>
<td>Vehicle Speed, m/sec</td>
<td>Desired Vehicle Speed, m/sec</td>
<td>Time Step, sec</td>
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<td>--------------------------</td>
<td>-------------</td>
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Table 6.6

HEADING FOR PERIODIC PRINTOUT
There is an error trapping routine in the program which is activated if mass in a working space is changed during Step 4 of the engine torque and internal heat transfer subprogram. Unless some changes are made this routine will not stop the program. If for some reason this routine is activated, the following message is printed out or displayed on the screens:

Flow error is ________ in working space # ____.

Following this is printed out or displayed 8 rows of 7 numbers which help determine where the problem is. The 8 rows are the eight nodes. Within each row the numbers give the following values from left to right.

1. Node number
2. Mass of gas in node at start of time step
3. Mass of gas in node at end of time step
4. Cumulative volumes in the solid
5. Cumulative volumes in the gas
6. Average gas temperature at the start of time step
7. Average gas temperature at the end of time step
The original expectation was that the solution using the programs described herein could be checked with the steady state power output and efficiency given by General Motors for the 4L23 machine (6). However, this was not done because the engine power output and efficiency were not calculated. It would not be difficult to add both power output calculation and the efficiency and heat balance calculation since most of the programming has already been done.

The input values for the base case are given in Tables 6.1, 6.2 and 6.3. Based upon this input the periodic output is given on Table 7.1. A line has been drawn to separate the periodic outputs. The key to what these numbers mean is given in Table 6.5.

Figure 7.1 shows the graphical output at the end of the solution of the base case. Figure 7.2 shows the solution part way along to show how the four pressure volume diagrams appear. Figure 7.3 shows how the screen looks with the display every time step superimposed. As an aid to interpreting what is seen on the screen, the data plotted on the screen are also plotted in Figure 7.4 using the data from Table 7.1.
Figure 7.2. Photograph of Graphical Output Part Way Through—Showing PV Diagrams.

Figure 7.3. Photograph of Final Solution with Display Line for Each Time Step Superimposed. (The display lines can be dimmed out for a better look at the graphics.)
Table 7.1

PERIODIC OUTPUT FOR BASE CASE
(See Table 6.5 for headings)

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<th>22.482</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.74</td>
<td>14.7</td>
<td>740.00</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Engine fuel flow = 3.74 g/sec. Engine speed = 70.4 radians/sec. Total engine revolutions = 740.
The identity of the lines on Figure 7.1 can be sorted out by comparing Figure 7.1 with Figure 7.4. Figure 7.4 is much less detailed since it is derived from Table 7.1 for every 5 seconds of real time.

Fuel flow is graphed in Figure 7.1 over the full vertical scale. A smaller scale was used in Figure 7.4. The fuel flow varies widely. It is at its maximum at the start as the engine is heating up and then at two other periods when the engine is working at full capacity. At the end of the driving cycle the fuel flow is still oscillating but appears to be damping out.

The top channel on the left in Figure 7.1 is for vehicle speed. The desired vehicle speed is drawn at the start of the solution. The calculated speed is superimposed upon this ramp and cruise. The calculated speed rushes ahead of the desired speed as the vehicle is put into first, second, and third gear. Possibly the engine has been assigned too much inertia. The vehicle coasts until the speed is back on schedule.

The next channel down on the left of Figure 7.1 is for engine speed. It attains idle speed within the two seconds before getting into gear. As the gear ratio changes in one second, there is very little reduction in engine speed. This is another indication of an unrealistically high engine inertia.

The final channel on the left is for engine and air preheater temperatures. The order of the temperatures from top to bottom soon after the engine starts are:

1. Flue gas leaving heater and entering preheater.
2. Flue gas leaving preheater.
3. Average heater metal.
4. Average mid-regenerator metal.
5. Average top of regenerator metal.
6. Average hot space metal.

These graphs show that the base case air preheater is inadequate and must be improved. The heater temperature takes a serious dip during second gear but recovers after the shift to third gear. Figure 7.4 shows that the calculated heater temperatures are quite different at the two ends. Half the heat from the burner is made to go to node #2 and half to node #3. There is a wide difference in temperature between these two nodes. Node #3 which is nearest the cold side of the engine is colder. After the engine reaches its cruise speed, there is a slow but pronounced divergence in individual node temperatures for nodes #2 and #3. Other metal node temperatures are less affected. Although data to this detail were only recorded every five seconds of real time, a particular heater node was always consistently high or low or in between. The author currently has no explanation for this behavior.

The next line down in Figure 7.1 has a sawtooth appearance. The temperature of metal node #5 at the midpoint of the regenerator rises when the engine pressure rises and falls when the engine pressure falls. The temperature falls at low pressure because conduction to the cold part of the engine is more important than convection from gas passing through the heater. This node attains its expected temperature midway between the heater and cooler. Note that the plotting of the individual node 5's during the acceleration phase indicates that this temperature cycles over about 50 K during an
engine cycle. Eventually this node temperature is lower than any of those plotted.

The next line in Figure 7.1 starts just below node 5 but is more stable. This is metal node 4 which is at the hot end of the regenerator. It is surprising that this node temperature settles out so close to the middle of the regenerator. This may be due to the low power the engine has to put out during cruise.

The final temperature line in Figure 7.1 is for metal node 1, the metal around the hot space. It starts out the lowest and ends up next to the lowest. One would expect that this node would attain heater temperature. However, at very low load like during cruise, heat conduction to the heat sink draws this temperature way down.

In conclusion, this computer program at this stage in its development gives reasonable looking answers. However, anyone who has worked with large computer programs knows there may be a number of important errors left in these programs.

Finally, the problem of the proper angle increment for the solution has not been resolved. With a 7 to 30 degree angle increment reasonable PV diagrams were drawn. It was feared that since the dead volume of the cooler is so small that with a 7 to 30 degree angle increment much gas might pass through the cooler in one time step without being affected by it. The only way to simulate transient thermal effects is to slow down the solution so that all the gas passing either way is affected by the cooler. To do this efficiently the angle increment limit should be made a variable and its effect should be investigated by a number of complete runs. Since each run takes all day, this work was left for the future.
8.0 CONCLUSIONS AND SUGGESTIONS FOR ADDITIONAL WORK

A computer program has been written and perfected and fully documented that will calculate the transient response of a Siemens arrangement Stirling engine similar to the General Motors 4L23 or the current United Stirling engines. Eighty-two different variables can be changed to adjust the solution to the needs of the calculator and the computer being used and to specify exactly the engine dimension and the operating condition for the engine and the vehicle.

The computer program models an engine which uses working gas pressure as a means of controlling power. The mode of controlling the heater tube temperature and either the engine or vehicle speed is by proportional control.

With this program as a basis the following additional tasks are suggested:

1. Determine the effect of having the four cylinders in unison instead of at 90° phase angle. The calculation normally goes for many hundreds if not thousands of revolutions. The effect on the driving cycle will probably not be significant but calculation speed would be quadrupled.

2. Obtain 16 steady state operating points after the program has been modified to have averaged power output and efficiency over a specified time period. Compare with a standard and make adjustment in the dimensions or other parameters.

3. Adapt the program to prediction of the transient performance of the Department of Energy Mod I engine in the vehicle that is planned for it. This will require finding all dimensions including thermal conductivities, moment of inertia, seal and mechanical friction, etc.

4. Compare this program and the version proposed in #1 above to that program published by Daniele and Lorenzo (4). Compare on the basis of solution time and accuracy.

5. Adapt either the current program or the one cylinder modification (#1 above) to a calculated, realistic heat transfer in all gas spaces. That is, the hot and cold spaces would not always be adiabatic and the heat exchangers would have the heat transfer coefficients expected for the instantaneous flow. Show how the gas and metal temperatures vary during the cycles.

6. Add variable stroke control to the program.

7. Predict the transient and steady state response of the Advenco engine now at NASA-Lewis.

This computer program was developed on a good quality microcomputer with high resolution graphic capabilities. With only the graphic output plus the single time display per time step the full base case of 90 seconds real time was run in 3 hours 45 minutes. The graphic display plus the printouts if desired would be adequate record of how well a particular method of control worked.
the single time display per time step the full base case of 90 seconds real
time was run in 3 hours 45 minutes. The graphic display plus the printouts
if desired would be adequate record of how well a particular method of con-
trol worked.
9.0 REFERENCES


APPENDIX A

TEST PROGRAM, WARM.FOR

Introduction

It was found that in order to perform a 90 second simulation of a simple driving cycle, it was necessary to repeat the calculation scheme approximately 35,000 times. The burner simulation is a significant part of the calculation scheme. Not only does it account for about one-fifth of the program lines, it also includes subroutine calls and multiple use of the exponential and log functions, all of which cause the computer to spend a large percentage of its executive time in this area. In order to reduce the 8 hour executive time required by the Altos computer and to simplify the main program, it was decided to attempt to create the WARM.FOR program. WARM.FOR would include the burner simulation from CNTLB.FOR, and would hopefully generate a simple relationship between burner efficiency and heat required by the heater tubes. CNTLB.FOR would then require only a few equations to predict fuel consumption as a function of engine heat requirement.

Node Arrays

One of the first modifications to the burner simulation was to increase the number of calculation nodes of the air preheater. Originally only four nodes were accounted for, but it was decided to use arrays instead of single variables. Tests were performed to determine the accuracy of the burner efficiency as a function of the number of nodes used in the calculation. It was found that by using 20 nodes, the calculated burner efficiency was within .1% of the efficiency calculated using 99 nodes. When using 99 nodes, the simulation requires 6% more time than the 20 node simulation requires. It was decided that .1% was not worth the prolonged calculation time. The four node simulation was about 7.5% lower so the 20 node simulation was used as a good compromise.

Time Increment

Regardless of the size of the program, if the calculations need to be executed twice as many times, then the time requirement doubles. A test was performed to determine how often burner calculations had to be made so that reasonably accurate numbers would be generated. It was found that by using .05, .1, and .5 second increments, the calculated burner efficiencies agree to 1% percent. However, when the one second time increment was used, the numbers generated became erratic and efficiencies of over 100% were calculated. As a result it was recommended that a .5 second time increment be used.

The results of the time increment and metal node test are shown in Table A1. A sample table generated by WARM.FOR for 20 nodes and .5 second increment is shown in Table A2.
Table A.1

BURNER EFFICIENCY AT START AND END OF 90 SECOND HEAT LOADS
(20 second warm-up)

<table>
<thead>
<tr>
<th>Calculation Nodes in Air Preheater Metal</th>
<th>Start</th>
<th>End</th>
<th>Start</th>
<th>End</th>
<th>Start</th>
<th>End</th>
<th>Start</th>
<th>End</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 Nodes</td>
<td>2500 W</td>
<td>70.9352</td>
<td>74.2632</td>
<td>70.9352</td>
<td>74.2863</td>
<td>70.9466</td>
<td>74.3302</td>
<td>115.7146</td>
</tr>
<tr>
<td></td>
<td>5000 W</td>
<td>56.6832</td>
<td>64.9165</td>
<td>56.6898</td>
<td>64.926</td>
<td>56.6207</td>
<td>64.9326</td>
<td>56.7153</td>
</tr>
<tr>
<td>4 Nodes</td>
<td>2500 W</td>
<td>73.7399</td>
<td>79.5016</td>
<td>73.7245</td>
<td>79.5016</td>
<td>73.6107</td>
<td>79.4766</td>
<td>304</td>
</tr>
<tr>
<td></td>
<td>5000 W</td>
<td>61.0833</td>
<td>72.2304</td>
<td>61.0749</td>
<td>72.2393</td>
<td>60.9241</td>
<td>72.2423</td>
<td>63.1280</td>
</tr>
<tr>
<td>8 Nodes</td>
<td>2500 W</td>
<td>75.5816</td>
<td>83.6796</td>
<td>75.5557</td>
<td>83.6637</td>
<td>75.3073</td>
<td>83.6161</td>
<td>1135</td>
</tr>
<tr>
<td></td>
<td>5000 W</td>
<td>63.4412</td>
<td>75.8706</td>
<td>63.4367</td>
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<td>75.8790</td>
<td>65.5192</td>
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<td>16 Nodes</td>
<td>2500 W</td>
<td>76.4958</td>
<td>85.9670</td>
<td>76.4826</td>
<td>85.9628</td>
<td>76.1591</td>
<td>85.9000</td>
<td>349</td>
</tr>
<tr>
<td></td>
<td>5000 W</td>
<td>64.2311</td>
<td>77.7706</td>
<td>64.2264</td>
<td>77.0773</td>
<td>64.0225</td>
<td>77.0773</td>
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</tr>
</tbody>
</table>

CALCULATION TIME INCREMENT

<table>
<thead>
<tr>
<th>.05 sec</th>
<th>.1 sec</th>
<th>.5 sec</th>
<th>1 sec</th>
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</thead>
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<tr>
<td>70.9352</td>
<td>74.2632</td>
<td>70.9352</td>
<td>74.2863</td>
</tr>
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<td>56.6832</td>
<td>64.9165</td>
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<td>72.2304</td>
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<td>64.2311</td>
<td>77.7706</td>
<td>64.2264</td>
<td>77.0773</td>
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<td>Calculation Nodes in Air Preheater Metal</td>
<td>Start</td>
<td>End</td>
<td>Start</td>
</tr>
<tr>
<td>-----------------------------------------</td>
<td>-------</td>
<td>--------</td>
<td>-------</td>
</tr>
<tr>
<td><strong>2500 W</strong></td>
<td>76.7254</td>
<td>86.5872</td>
<td>76.3899</td>
</tr>
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</tr>
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<td>76.8557</td>
<td>86.9199</td>
<td>76.5091</td>
</tr>
<tr>
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<td>64.2498</td>
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<td>76.5357</td>
<td>86.9377</td>
<td></td>
</tr>
<tr>
<td>64 Nodes</td>
<td></td>
<td></td>
<td>74.2662</td>
</tr>
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</table>

CALCULATION TIME INCREMENT

1 sec | .5 sec
Table A.2

WARM FOR OUTPUT

20 Nodes
.5 sec Time Increment

<table>
<thead>
<tr>
<th>TIME (SEC)</th>
<th>HT TUBE (K)</th>
<th>FUEL FLOW (G/S)</th>
<th>HEAT REQ (W)</th>
<th>BURNER EFF</th>
<th>APH MELT NODE</th>
<th>APH HT BFL %</th>
</tr>
</thead>
<tbody>
<tr>
<td>.50</td>
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<td>0.0000</td>
<td>729.4823</td>
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</tr>
<tr>
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<td>1767.7417</td>
<td>-45.3196</td>
</tr>
</tbody>
</table>
Burner Correlation

In order to simplify the burner calculations for the CNTLB.FOR program, two correlations were necessary:

1. burner efficiency as a function of engine heat requirement.
2. burner efficiency as a function of time after the heat requirement changes significantly (transient condition).

The second correlation was attempted first, using WARM.FOR a 1000 second duration. The burner efficiency was calculated as a function of time for a 20 second warm up and one constant heat requirement. Three points were taken from the first 100 seconds of simulation and an effort was made to discover a function described by the three points that would indicate the burner efficiency at 1000 seconds. Two methods were used, a power curve fit using the IF - 67 curve fitting routine and a more direct method involving the solving of three simultaneous equations with three unknowns. The results are shown in Figure A.1. A non-linear extrapolation of this size is, of course, very difficult. Since the closest correlation was 2% off for this simple example, it was decided that the burner calculations should be an integral part of the main control program (CNTLB.FOR) if any reasonable accuracy is desired.

![Figure A.1. Burner Efficiency Versus Time.](image-url)
Utility of WARM.FOR

Although WARM.FOR cannot be used to generate a simple correlation for use in CNTLB.FOR, it can be used to determine burner efficiencies and air preheater temperatures as a function of time for various heat requirements. Of most value are the plots of various burner temperatures and burner efficiency as a function of time. A worthwhile addition to the program would be to calculate the heat requirement of the other metal parts of the engine as warm up occurs.

Input

A sample table and the glossary of input variables are shown in Table A3. Changes are made by typing the item number, a space, then the new value, including a decimal point. QL is assigned the value of 1 if a table output such as Table A2 is desired. DTO determines the frequency of data printout. TTT is the duration of each heat requirement. The heat requirement is set during the warm up time, and is increased by HREQ each time a period lasting TTT seconds is finished. The simulation lasts TOTT seconds. Hash marks divide the total simulation time into tenths.

Graphical Output

A diagram of a typical graphical output is shown in Figure A.2. The top section plots various burner temperatures. The bottom section plots burner efficiency and fuel flow as a function of maximum fuel flow. The left side of the screen displays digital values of what is presented graphically on the right side. The air preheater balance (APH BAL) describes the balance of energy between heat transfer from the flue gas to the air preheater metal and heat transfer from the air preheater metal to the inlet gas. A negative balance indicates that more heat is being transferred to the metal than from the metal, so its temperature must be rising.

Program Listing

The program listing of WARM.FOR now follows. Note that the listing contains its own nomenclature and its own method of changing input variables similar to CNTLA given in the body of the report.
### Table A.3

**WARM FOR SAMPLE TABLE AND GLOSSARY OF TABLE VARIABLES**

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<thead>
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<th>OPERATING CONDITIONS BY NUMBER</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>01 922 200 * 02 50,000</td>
<td>03 300,000 * 04 .500 * 05 10,000</td>
<td></td>
</tr>
<tr>
<td>06 20,000 * 07 20 * 08100000</td>
<td>09 90,000 * 10 200,000</td>
<td></td>
</tr>
<tr>
<td>11 1 * 12 10,000 * 13 0,000 * 14 0,000 * 15 0,000</td>
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<td></td>
</tr>
<tr>
<td>16 0,000 * 17 0,000 * 18 0,000 * 19 0,000 * 20 0,000</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**ENGINE DIMENSIONS**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>21 10,000 * 22 5,000 * 23 200</td>
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</tr>
<tr>
<td>26 16,550 * 27 640 * 28 472</td>
<td>29 25,580 * 30 2</td>
</tr>
<tr>
<td>31 2,500 * 32 200 * 33 0  * 34 0,000 * 35 0,000</td>
<td></td>
</tr>
<tr>
<td>36 0,000 * 37 0,000 * 38 0,000 * 39 0,000 * 40 0,000</td>
<td></td>
</tr>
</tbody>
</table>

---

1. THMG, °K
2. TPB, °K
3. T1, °K
4. DT, sec
5. FFF, g/s
6. THU, sec
7. NO
8. HREQ, watts
9. TTT, sec
10. TOTT, sec
11. Q1
12. DTO, sec
13. LAPH, cm
14. WAPH, cm
15. NAPH
16. TMAPH, cm
17. TAPH, cm
18. RAF
19. DOH, cm
20. DIH, cm
21. LHH, cm
22. MTH
23. LR, cm
24. FF
25. NS
26. MSH, wires/cm
Inlet Air Temp.

Cold Node  Hot Node
300. 481.
*  *
1472. 2297.

Exhaust Temp.

BURN EFF 0.0 APH BAL-464.6 CFF 10.000

300. 962.
* * 694. 843. 1051. * 3166.
* * 791. 2232.

BURN EFF 0.0 APH BAL-169.1 CFF 1.503

300. 1089.
* * 653. 844. 1116. * 3294.
* * 675. 1610.

BURN EFF 76.3 APH BAL -46.4 CFF 282

300. 1136.
* * 619. 845. 1171. * 3341.
* * 649. 1612.

Figure A.2. Sample Graphics Screen.
### Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Temporary variable</td>
</tr>
<tr>
<td>AAPH</td>
<td>Heat transfer area of full air preheater, sq cm</td>
</tr>
<tr>
<td>ACE</td>
<td>Radial engine acceleration, rad/sec^2</td>
</tr>
<tr>
<td>ACV</td>
<td>Acceleration of vehicle at start of time step, m/sec^2</td>
</tr>
<tr>
<td>ACY</td>
<td>( \pi^4 \cdot DCY^2 )</td>
</tr>
<tr>
<td>AF</td>
<td>Friction, newton</td>
</tr>
<tr>
<td>AL</td>
<td>Air preheater energy balance, ( HTA-HTF+HTA )</td>
</tr>
<tr>
<td>B</td>
<td>Temporary variable</td>
</tr>
<tr>
<td>BCY</td>
<td>( \pi^4 \cdot DCY^2 - DDR^2 )</td>
</tr>
<tr>
<td>BEF</td>
<td>Burner efficiency, %</td>
</tr>
<tr>
<td>C</td>
<td>Coefficient for shape of vehicle</td>
</tr>
<tr>
<td>CMAPH</td>
<td>Heat capacity of full air preheater, J/°K</td>
</tr>
<tr>
<td>CMH</td>
<td>Heat capacity of gas heaters for one cylinder, J/°K</td>
</tr>
<tr>
<td>CMX</td>
<td>Heat capacity of regenerator matrix, J/°K</td>
</tr>
<tr>
<td>CP</td>
<td>Heat capacity at constant pressure, J/°K</td>
</tr>
<tr>
<td>CPA</td>
<td>Heat capacity of air, J/°K</td>
</tr>
<tr>
<td>CFPG</td>
<td>Heat capacity of flue gas, J/°K</td>
</tr>
<tr>
<td>CS</td>
<td>Coefficient for shape of vehicle</td>
</tr>
<tr>
<td>CV</td>
<td>Heat capacity at constant volume, J/°K</td>
</tr>
<tr>
<td>CYY</td>
<td>( 4 \cdot \pi^2 \cdot DT \cdot CMAPH )</td>
</tr>
<tr>
<td>DANG</td>
<td>Change in engine angle, rad</td>
</tr>
<tr>
<td>DCY</td>
<td>Diameter of cylinder, cm</td>
</tr>
<tr>
<td>DDR</td>
<td>Diameter of drive rod, cm</td>
</tr>
<tr>
<td>DEQ</td>
<td>Equivalent diameter (used in air preheater), cm</td>
</tr>
<tr>
<td>DIC</td>
<td>Diameter inside of cooler tubes, cm</td>
</tr>
<tr>
<td>DIH</td>
<td>Diameter inside of heater tubes, cm</td>
</tr>
<tr>
<td>DST</td>
<td>Distance traveled from start, m</td>
</tr>
<tr>
<td>DOH</td>
<td>Outside diameter of heater tubes, cm</td>
</tr>
<tr>
<td>DR</td>
<td>Diameter of each regenerator, cm</td>
</tr>
<tr>
<td>DST</td>
<td>Distance traveled during time step, m</td>
</tr>
<tr>
<td>DT</td>
<td>Time step, sec</td>
</tr>
<tr>
<td>EADEG</td>
<td>Engine angle, degrees</td>
</tr>
<tr>
<td>ERRAD</td>
<td>Engine angle, radians</td>
</tr>
<tr>
<td>EIN</td>
<td>Engine inertia, N m^2</td>
</tr>
<tr>
<td>EX&lt;20&gt;</td>
<td>Air preheater metal node temperatures, K</td>
</tr>
<tr>
<td>FCA</td>
<td>Fraction of VCDX that is adiabatic</td>
</tr>
<tr>
<td>FF</td>
<td>Filler factor, fraction of regenerator volume filled with solid; must be zero if it is not used</td>
</tr>
<tr>
<td>FFF</td>
<td>Full fuel flow, g/s</td>
</tr>
<tr>
<td>FLAME</td>
<td>Burner flame temperature, K</td>
</tr>
<tr>
<td>FP&lt;4&gt;</td>
<td>Force on pistons (away from crankshaft is positive)</td>
</tr>
<tr>
<td>FWI</td>
<td>Flow, water inlet for entire engine, g/sec</td>
</tr>
</tbody>
</table>
GA = (KK-1)/KK

GMAX = MAXIMUM MASS VELOCITY IN HEATER, G/S CM**2

HAS = HEAT TRANSFER COEFFICIENT, W/K CM**2

HREQ = ENGINE HEAT LOAD, WATTS

HTA = HEAT RECEIVED BY ENTERING AIR, J/G

HTG = HEAT REJECTED BY FLUE GAS, J/G

IG1 = VEHICLE CONTROL FLAG, 1=REMOVE MASS 2=ADD MASS

IL12 = GRAPHIC OUTPUT, X VALUES

ILJ2 = GRAPHIC OUTPUT, Y VALUES

J7 = DETERMINES INPUT NUMBER SELECTION

KAR = COEFFICIENT OF AIR RESISTANCE

KX = CP/CV

KR = 1 / KK

KRR = COEFFICIENT OF ROLLING RESISTANCE

LAPH = HEAT TRANSFER LENGTH IN AIR PREHEATER, CM

LC = LENGTH OF COOLER TUBES, CM

LCR = LENGTH OF CONNECTING ROD, CM

LH = LENGTH OF HEATER TUBES, CM

LHH = HEATED LENGTH OF HEATER TUBES, CM

LHV = LOWER HEATING VALUE OF FUEL, J/G

LR = LENGTH OF REGENERATOR, CM

M(4) = INVENTORY OF GAS IN EACH ENGINE COMPARTMENT, G

ME = ENGINE MECHANICAL EFFICIENCY, PERCENT

MEG = INITIAL GAS INVENTORY, G

MIR = FACTOR RELATING MASS FLOW TO PRESSURE DROP, G/S MPA

MIR1 = ADJUSTMENT OF MIR TO PREVENT CONTROL OVERSHOOT

MIV = MASS, INERTIA OF VEHICLE, KG

MSH = MESH SIZE, WIRES/CM

MW = MOLECULAR WEIGHT OF WORKING GAS, G/G MOLE

MWFG = MOLECULAR WEIGHT OF FLUE GAS, G/G MOLE

NAPH = NUMBER OF AIR PREHEATER FLOW PASSAGES IN EACH DIRECTION

NR = NUMBER OF REGENERATORS/CYLINDER

NS = NUMBER OF SCREENS PER REGENERATOR

NTC = NUMBER OF COOLER TUBES/CYLINDER

NTH = NUMBER OF HEATER TUBES PER COMPARTMENT

OM1 = DESIRED IDLE SPEED OF ENGINE, R/S

PI = PI = 3.141592654

PI2 = PI/2 = 1.570796327

P132 = 3*PI/2

PI4 = PI / 4 = .7853981635

PRH = HIGH PRESSURE RESERVOIR PRESSURE, MPA

PRL = LOW PRESSURE RESERVOIR PRESSURE, MPA

P1(4) = GAS PRESSURE AT BEGINNING OF TIME STEP, MPA

P2(4) = GAS PRESSURE AFTER VOLUME CHANGE, MPA

P3(4) = GAS PRESSURE AFTER TEMPERATURE EQUILIBRATION AT CONSTANT VOLUME, MPA

P4(4) = COMMON GAS PRESSURE AT END OF TIME STEP, MPA

QH = HEATING OF HEATER TUBES OF ONE CYLINDER BY BURNER

QHI(4) = CUMULATIVE HEAT INPUT FOR CYCLE, J

QEX = HEATING OF WORKING GAS IN HEATER TUBES DURING TIME STEP, J
106: C Q1 = OUTPUT FLAG. 1=FULL OUTPUT  2=QUICK RUN
107: C R = 8.314 J/G MOl K
108: C RAD = 0.017453 RADIANS/DEGREE
109: C RAF = RATIO OF AIR TO FUEL, G/G
110: C RAf = RAF+1, G/G
111: C RC = RADIUS OF CRANK, CM
112: C RC2 = 2*RC
113: C RE = REYNOLDS NUMBER
114: C RF = ROLLING FRICTION, NEWTONS
115: C RGE = RATIO OF GEARS, VEHICLE TRAVEL/REV. METERS
116: C RX = CP - CV
117: C SPM = CRUISING SPEED OF VEHICLE, M/S
118: C SPVD = VEHICLE SPEED DESIRED BY SCHEDULE, M/S
119: C SS = SPEED OF VEHICLE AT BEGINNING OF TIME STEP, M/SEC
120: C ST = 1 TO CONTINUE, 2 TO START OVER
121: C STN = STANTON NUMBER TIMES PRRNDL NICER TO TWO THIRDS POWER
122: C T1 = AMBIENT AIR TEMPERATURE, K
123: C TA = AVERAGE OF HEATER METAL TEMPERATURES, K
124: C TAC = VEHICLE ACCELERATION TIME, SEC
125: C T2 = CRANKING TIME AFTER INLET BURNER, SEC
126: C TAP = TIMELAPSE OF PREHEATER PASSAGE, CM
127: C CCR = DURATION OF STARTING MOTOR TORQUE, SEC
128: C GC(2,4) = TEMPERATURE OF GAS IN COOLER, K
129: C GCX(2,4) = TEMPERATURE OF GAS IN COLD SPACE AND DUCT, K
130: C GC(2,4) = TEMPERATURE OF COLD METAL IN COOLER, K
131: C TF = TIME INCREMENT FLAG. 0=DOUBLE INCREMENT, 1=NO CHANGE.
132: C 2=HALF INCREMENT
133: C TH(2,4) = TEMPERATURE OF GAS IN HEATER, K
134: C THS(2,4) = TEMPERATURE OF GAS IN HOT SPACE, K
135: C THD(2,4) = TEMPERATURE OF GAS AT REGENERATOR MIDPOINT, K
136: C THW = THICKNESS OF WIRE IN SCREENS OF REGENERATOR CM
137: C TMH(2,4) = TEMPERATURE OF HOT METAL IN HEATER, K
138: C THG = TEMPERATURE OF HOT METAL GOAL, K
139: C THU = ENGINE HARM-UP TIME, SEC
140: C TI1 = THU+TCC
141: C TI2 = THU+TID
142: C TII = TI1+TCR
143: C TII = TI1+TID
144: C TII = TI1+TAC
145: C TMAH = THICKNESS OF METAL SEPARATING EACH FLOW PASSAGE, CM
146: C TMAP(2,4) = MIDPOINT TEMPERATURE OF REGENERATOR MATRIX, K
147: C TNET = NET ENGINE TORQUE, N-M
148: C TOTT = TOTAL SIMULATION TIME, SEC
149: C TUG(2,4) = FLUE GAS NOSE TEMPERATURES, K
150: C TFB = TEMPERATURE, PROPORTIONAL BAND IN HOT METAL, K
151: C TFU = INTERVAL BETWEEN PRINT OUTF'S, S
152: C TGO = TORQUE FROM EACH PISTON. CCW IS POSITIVE. N-M
153: C TOI = TOTAL INDICATED TORQUE. N-M
154: C TOS = TOTAL SHAFT TORQUE. N-M
155: C TGV = TORQUE VEHICLE PUTS ON ENGINE. N-M
156: C TRAY = AVERAGE REG. METAL TEMP. K
157: C TST = STARTING MOTOR TORQUE, N-M
TT = CHECK TO DETERMINE WHEN POINTS SHOULD BE PLOTTED
TWI = TEMPERATURE, WATER INLET, K
TWO = TEMPERATURE OF COOLING WATER, K
UAPH = HEAT TRANSFER COEFF. AIR TO METAL IN AIR PREHEATER, W/CM² K
UH = HEAT TRANSFER COEFF. FLUE GAS TO GAS HEATER METAL, W/CM² K
UXX = UV/CY
VAB = VOLUME OF AIR IN BURNER, CU CM
VCA(2,4) = VOLUME, COLD, ADIABATIC, START AND END OF TIME STEP
VCA(1,4) = VOLUMES OF GAS ORIGINALLY IN ADIABATIC COLD SPACE
VCD = VOLUME, COLD DEAD, CU CM
VCD(4) = VOLUMES OF GAS ORIGINALLY IN GAS COOLER AND ISOTHERMAL PART OF COLD DUCT AFTER VOLUME CHANGE
VCDX = VOLUME, COLD DEAD NOT IN GAS COOLER, CU CM
VCHAD(2,4) = VOLUME, HOT, ADIABATIC, START AND END OF TIME STEP
VCHAD(1,4) = VOLUMES OF GAS ORIGINALLY IN HOT ADIABATIC SPACE AFTER VOLUME CHANGE, CU CM
VCHAD(1) = EXTRA HOT VOLUME BESIDES THAT IN THE GAS HEATER, CU CM
VC CM = INCLUDES END CLEARANCE, GAP AROUND HOT CAP AND MANIFOLD, ASSUMED AT HOT METAL TEMPERATURE
VCDR = VOLUME, REGENERATOR DEAD, PER CYLINDER, CU CM
VCDR(4) = VOLUMES OF GAS ORIGINALLY IN REGENERATOR AFTER VOLUME CHANGE, CU CM
VT(2,4) = TOTAL GAS VOLUMES AT START AND END OF TIME STEP, CU CM
VD = TOTAL DEAD VOLUME, CU CM
WAPH = WIDTH OF EACH AIR PREHEATER PASSAGE, CM
WCA(2,4) = MASS IN ADIABATIC COLD SPACE AT START AND END, G
WCD(2,4) = MASS IN ISOTHERMAL COLD SPACE AT START AND END, G
WCHAD(2,4) = MASS IN ADIABATIC HOT SPACES AT START AND END, G
WCHAD = MASS IN HOT DEAD SPACE, G
WFC = MASS OF REGENERATOR GAS MOVING INTO COOLER, G
WFP(2,4) = MASS IN REGENERATOR DEAD SPACE AT START AND END, G
WPH = MASS OF REGENERATOR GAS MOVING INTO HEATER, G
U = TEMPORARY VARIABLE
x = VOLUME RATIO
X = Wrapper for volume ratio
X = ENGINE SPACINGS IN 4 CYLINDER MACHINE
X = " " " "
X = " "
X = " "
X = E Flow (1/0): 1 FOR HIGH FLOW THROUGH PREHEATER

**** START OF PROGRAM ****
DIMENSION THM(4), TCM(4), TGH(2,4), TGC(2,4), TIN(50).

1 EX(50), TOU(50), TMN(4), OHI(4), TGH(4)

INTEGER 01, ST

REAL LH, LR, LS, MFG, LAFH, LHH, LIV, MSH

C INITIAL OPERATING CONDITIONS

DATA THM(4), TCM(4), TGH(2,4), TGC(2,4), TIN(50).

DATA LH, LR, LS, MFG, LAFH, LHH, LIV, MSH.

C ENGINE DIMENSIONS

DATA DCY, DOR, NS(4), N.

C DATA VMID, DII, LTH, NTH.

C DATA WR, WRH, WRH, WRH, TMAFH, TAPH, RAF, NTH

C DATA LHH, LHH, LHH, MTH

C DATA LAPH, WAPH, TAPH, RAF, NTH

C DATA COK, COK

C DATA P1, P1, P1

WRITE(J, 1)

FORMAT(15X, 5, 5)

WRITE(J, 2)

FORMAT(15X, 5, 5)

WRITE(J, 3)

FORMAT(15X, 5, 5)

WRITE(J, 4)

FORMAT(15X, 5, 5)

WRITE(J, 5)

FORMAT(15X, 5, 5)

WRITE(J, 6)

FORMAT(15X, 5, 5)

WRITE(J, 7)

FORMAT(15X, 5, 5)

WRITE(J, 8)

FORMAT(15X, 5, 5)

WRITE(J, 9)

FORMAT(15X, 5, 5)

WRITE(J, 10)

FORMAT(15X, 5, 5)

WRITE(J, 11)

FORMAT(15X, 5, 5)

WRITE(J, 12)

FORMAT(15X, 5, 5)

WRITE(J, 13)

FORMAT(15X, 5, 5)

WRITE(J, 14)

FORMAT(15X, 5, 5)

WRITE(J, 15)

FORMAT(15X, 5, 5)

WRITE(J, 16)

FORMAT(15X, 5, 5)

WRITE(J, 17)

FORMAT(15X, 5, 5)

WRITE(J, 18)

FORMAT(15X, 5, 5)

WRITE(J, 19)

FORMAT(15X, 5, 5)

WRITE(J, 20)

FORMAT(15X, 5, 5)

WRITE(J, 21)

FORMAT(15X, 5, 5)

WRITE(J, 22)

FORMAT(15X, 5, 5)

WRITE(J, 23)

FORMAT(15X, 5, 5)

WRITE(J, 24)

FORMAT(15X, 5, 5)

WRITE(J, 25)

FORMAT(15X, 5, 5)

WRITE(J, 26)

FORMAT(15X, 5, 5)

WRITE(J, 27)

FORMAT(15X, 5, 5)

WRITE(J, 28)

FORMAT(15X, 5, 5)

WRITE(J, 29)

FORMAT(15X, 5, 5)

WRITE(J, 30)

FORMAT(15X, 5, 5)

WRITE(J, 31)

FORMAT(15X, 5, 5)

WRITE(J, 32)

FORMAT(15X, 5, 5)

WRITE(J, 33)

FORMAT(15X, 5, 5)

WRITE(J, 34)

FORMAT(15X, 5, 5)

WRITE(J, 35)

FORMAT(15X, 5, 5)

WRITE(J, 36)

FORMAT(15X, 5, 5)

WRITE(J, 37)

FORMAT(15X, 5, 5)

WRITE(J, 38)

FORMAT(15X, 5, 5)

WRITE(J, 39)

FORMAT(15X, 5, 5)

WRITE(J, 40)

FORMAT(15X, 5, 5)

WRITE(J, 41)

FORMAT(15X, 5, 5)

WRITE(J, 42)

FORMAT(15X, 5, 5)

WRITE(J, 43)

FORMAT(15X, 5, 5)

WRITE(J, 44)

FORMAT(15X, 5, 5)

WRITE(J, 45)

FORMAT(15X, 5, 5)

WRITE(J, 46)

FORMAT(15X, 5, 5)

WRITE(J, 47)

FORMAT(15X, 5, 5)

WRITE(J, 48)

FORMAT(15X, 5, 5)

WRITE(J, 49)

FORMAT(15X, 5, 5)

WRITE(J, 50)

FORMAT(15X, 5, 5)
263: GO TO (82, 83, 84, 85, 86, 87, 88, 89, 90, 91), J7
264:  51  J7=G7-39
265: GO TO (92, 93, 94, 95, 96, 97, 98, 99, 100, 101), J7
266:  53  THING=QQ
267:  GOT09
268:  54  TPB=QQ
269:  GOT09
270:  55  T1=QQ
271:  GOT09
272:  56  DT=QQ
273:  GOT09
274:  57  FFF=QQ
275:  GOT09
276:  58  THU=QQ
277:  GOT09
278:  59  ND=QQ
279:  GOT09
280:  60  HREQ=QQ
281:  GOT09
282:  61  TTT=QQ
283:  GOT09
284:  62  TOTT=QQ
285:  GOT09
286:  63  Q1=QQ
287:  GOT09
288:  64  TPO=QQ
289:  GOT09
290:  65  GN=QQ
291:  GOT09
292:  66  GN=QQ
293:  GOT09
294:  67  GN=QQ
295:  GOT09
296:  68  GN=QQ
297:  GOT09
298:  69  GN=QQ
299:  GOT09
300:  70  GN=QQ
301:  GOT09
302:  71  GN=QQ
303:  GOT09
304:  72  GN=QQ
305:  GOT09
306:  73  LPAP=QQ
307:  GOT09
308:  74  NPAP=QQ
309:  GOT09
310:  75  NPAP=QQ
311:  GOT09
312:  76  TPAP=QQ
313:  GOT09
314:  77  TAP=QQ
315:  GOT09
CONTINUE
IF(1.0 GE 1.0) WRITE(2,195)
195 FORMAT(1X,16H1) ** BURNER EFF.: APH MET NOCE: APH HT BAL: **
1 ** ********** BURNER INITIALZATION **********
DO 200 I=1,10
200 EXIT=1.0
C HEAT CAPACITY OF AIR PREHEATER METAL ASSUMING STEEL WITH
C 500 J/CU CH K HEAT CAPACITY
CMAPH=LAPH+WAPH+2.*NAPH+TAPH+2.5
C FLOW AREA IN PREHEATER
AFAPH=WAPH+TAPH+NAPH
C HEAT TRANSFER CONSTANTS
RA1=RAF+1
CZ=CPFG+RA1
DEO=2.*NAPH+TAPH/\(NAPH+TAPH\)
USV=LAPH+WAPH+2.*NAPH/(NO+CZ)
DT2=LV/CZ
CV=CPA+RAF+NO/CMAPH
USC=LAPH+WAPH+2.*NAPH/(NO+RAF+CPA)
CV=CVZ+NO/CMAPH
FUEL=0
C MINIMUM FLOW AREA FOR FLUE GAS THROUGH GAS HEATER
AMF=COH+LHH*NTH+2.
C HEAT TRANSFER AREA TO PLANE FOR COMPLETE ENGINE
AH=AMF+2*PI
C HEAT CAPACITY OF GAS HEATER FOR ONE CYLINDER
CMH=4.*PI+\(COH+2*DIH+2\)*LHH*NTH
C INITIALIZE CUMULATIVE HEAT INPUT
DO 198 I=1,4
198 THM=1=TI
DO 198 0H1=1=0
DO 198 DEI=0
DO 198 TI=0
DO 198 THI=0
CALL CLEAR
100 XI=512
120 XI=0
400 XI=100
400 XI=0
400 CALL VECTOR: XI, XI, XI, XI
405 XI=100
406 XI=778
407 CALL VECTOR: XI, XI, XI, XI
408 XI=512
409 XI=778
410 CALL VECTOR: XI, XI, XI, XI
411 XI=512
411 XI=0
411 CALL VECTOR: XI, XI, XI, XI
414 XI=500
415 XI=400
416 XI=100 I=1-11
417 XI=5 I=1-54
417 XI=11
419 X90 CALL VECTOR: XI, XI, XI, XI
419 NO=NO+1
421 TIN(1)=T1
422 C ********** GAS HEATER WARM UP **********
424 TIN=TIN+DT
425 T=THM(1)+THM(2)+THM(3)+THM(4)+T"4
426 C TEMPERATURE ERROR FOR CONTROL
427 C CURRENT FUEL FLOW
428 IF(TE-405.405)<0.06
429 CFF=0.01*FFF
430 GOTO409
431 IF(TE-TFB-400.400)<0.07
432 CFF=FFF
433 GOTO409
434 CFF=FFF*(TE)/TPB
435 CONTINUE
436 FUEL=FUEL+CFF*DT
437 C HEAT TRANSFER CALCULATIONS
438 C AIR TEMPERATURES
439 C HEAT TRANSFER COEFFICIENT
440 GRAPH=CFF*RAF/AFAPH
441 RE=DEQ*GRAPH+2500
442 CALL STANTNR(Re,STN)
443 X=U0*STN*GRAPH+1.19/CFF
444 IF(32-X)420,420,425
445 DO I=1,N0
446 IF(TE-784)<0.07
447 CFF=FFF
448 GOTO409
449 CFF=FFF*(TE)/TPB
450 CONTINUE
451 FUEL=FUEL+CFF*DT
452 C ADJUST HEAT EXCHANGER METAL TEMPERATURES
453 X=CY*CFF*DT
454 DO I=1,N0
455 EX(I)=EX(I)-X*(TIN(I+1)-TIN(I))
456 FLAME=TIN(NO)+TNO+DT
457 C HEAT FLUX TO ALL HEATERS
458 C OUTSIDE CONTROLLING HEAT TRANSFER COEFFICIENT
459 UH=(OH*CRF/RAL/AFPH/0006)==0.5*0002/DH
460 DO I=1,4
461 IF(CFF-X)435,435,437
462 X=UH*AH*(CZ+32)
463 IF(CFF-X)435,435,437
464 GOTO438
465 T3A(I)=THM(I)
466 CONTINUE
467 X=TE*(T3A(I)+T3A(2)+T3A(3)+T3A(4))/4
468 C EXIT FLUE GAS TEMPERATURES THROUGH AIR PREHEATER
469 C HEAT TRANSFER COEFFICIENT, FLUE GAS SIDE
470 GRAPH=CFF*(RAH/AFAPH
471 RE=DEQ*GRAPH+2500
472 CALL STANTNR(RE,STN)
473 X=STN*GRAPH+1.19/UHX/CFF
474 IF(X-32)444,444,440
475 146
475 440  DO 442 I=1,NO
475 442  TOU(I)=EX(I)
477 444  GOTO446
478 444  X=EXP(X)
479  446  DO446 I=1,NO
480  446  J=NO+1
481  446  TOU(J)=EX(J)-(EX(J)-TOU(J+1))
482  447  C READJUST AIR PREHEATER METAL TEMPERATURE
483  448  X=CYY+FF*T
484  450  DO 450 I=1,NO
485  450  EX(I)=EX(I)+(EX(I)-TOU(I+1)-TOU(I))
486  451  C TEMPERATURE EQUILIBRATION FOR TIME STEP WITH NO VOLUME CHANGE
487  452  C --TO SHORTEN CALCULATION IT IS ASSUMED THAT HEAT TRANSFER IN THE
488  453  C HOT AND COLD SPACES IS NON-EXISTANT AND THE HEAT TRANSFER
489  454  C IN THE OTHER SPACES IS PERFECT
490  455  C IN GAS HEATERS
491  456  C BURNER HEATING
492  489  DO 489 I=1,4
493  489  OE=LT*(2*FF+FLAME+TSA(T))/4.
494  490  IF(IE LT 2)GOTO489
495  495  C CUMULATIVE HEAT INPUT FOR CYCLE
496  496  OHI(I)=OHI(I)+OE
497  497  C CHANGE IN TEMPERATURE OF HEATER METAL
498  489  THM(I)=THM(I)+OE-OEX)/CMH
499  500  BEF=OE*V/((FF+LHV)+400
500  501  J=TIM*TOTT+450+54
501  502  CALL POINT(I,J)
502  503  J=20*(TA-300)+410
503  504  CALL POINT(I,J)
504  505  J=20*(EX(NO)-300)+410
505  506  CALL POINT(I,J)
506  507  J=20*(EX(I)-300)+410
507  508  CALL POINT(I,J)
508  509  J=FF*V/550+20
509  510  CALL POINT(I,J)
510  511  IF(TIT-570,505,505
511  512  505  TT=TT+TPO
512  513  HTA=CFH+RAF*(TIN(NO+1)-TIN(I))
513  514  HTF=PFG+RRF*(TOU(NO+1)-TOU(I))
514  515  IF(HTA LT 99 )GOTO518
515  516  BAL=HTA-HTF
516  517  BAL=188.
517  518  WRITE(5,518)BEF, BAL, FF
518  519  WRITE(5,519)TIM, TA, FF, BEF, EX(NO), BAL
519  520  WRITE(5,517)TIM(I), TIN(NO+I), EX(I), EX(NO+I), EX(NO), FLAME
520  521  1 TOU(I), TOUT(NO+I)
522  523  WRITE(5,516)BEF, BAL, FF
523  524  518  FORMAT(.DOGE 1,WRITE(2.519)TIM, TA, FF, BEF, EX(NO), BAL
524  525  X=OE/DT
525  526  IF(TIM GE 1,WRITE(2,519)TIM, TA, FF, BEF, EX(NO), BAL

147
527: 519 FORMAT(' ',F8.2,F17.4,F14.4,F14.4)
528: 520 IF(TIM=THU)400,400,540
529: 540 GEN=GEN+RE0*DT/4.
530: IF(TIM.GT.TOTT)GOTO600
531:  THU=THU+TTT
532:  GOTO400
533: 600 READ(5,610)X
534: 610 FORMAT(F10.2)
535:  GOTO9
536: 5000 STOP
537:  END
538:  SUBROUTINE STANTN(RE,STN)
539:  IF(RE=2000.)100,100,200
540:  100 STN=EXP(-9.956-9.956*ALOG(RE))
541:  GOTO300
542:  200 STN=EXP(-4.0555-1.803*ALOG(RE))
543:  RETURN
544:  END
APPENDIX B

SHAFT TORQUE CORRELATION

The shaft torque is lower than the indicated torque due to two friction losses; mechanical friction and flow losses inside the engine. Flow losses can be calculated using fluid mechanics principles, but for the sake of simplicity, it was desired to derive a correlation that would approximate engine flow loss at various speeds and working gas pressures.

ISO.FOR is a computer code developed by Martini Engineering (6) that calculates flow losses in the heater, regenerator and cooler of the 4L23 engine using fluid mechanics principles. The program was executed 16 times, with four pressures ranging from 1.38-9.66 MPa and four speeds ranging from 3.33 to 33.3 Hz. The ratios of net torque (indicated less the flow losses) to indicated torque were plotted for the 16 cases and are shown in Figure B.1. The full input and output of these cases are given in Table B.1.

It was noted that the flow losses increased with speed and decreased with pressure. The effect of pressure on the flow loss increases with speed. It was decided to use these two relationships to determine the flow loss correlation.

![Figure B.1. Torque Ratio for Various Pressures and Speeds.](image-url)
### Table B.1

FULL INPUTS AND OUTPUTS FOR 16 CASES
USED TO DERIVE TORQUE CORRELATION

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Meaning and units</th>
</tr>
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<tbody>
<tr>
<td>SP</td>
<td>Engine Speed, rpm</td>
</tr>
<tr>
<td>PS</td>
<td>Average Pressure, psia</td>
</tr>
<tr>
<td>ND</td>
<td>Number of degrees in angle increment</td>
</tr>
<tr>
<td>TF</td>
<td>Inside Heater Tube Wall Temperature, F</td>
</tr>
<tr>
<td>L1</td>
<td>Fraction of Total Gas Charge Leakage per MPaAP per second</td>
</tr>
<tr>
<td>TY</td>
<td>Inlet Cooling Water Temperature, F</td>
</tr>
<tr>
<td>FX</td>
<td>Cooling Water Flow gpm @ 2000 rpm per cylinder</td>
</tr>
<tr>
<td>OG</td>
<td>Operating Gas, 1 = hydrogen, 2 = helium, 3 = air</td>
</tr>
<tr>
<td>DC</td>
<td>Diameter of engine cylinder, cm</td>
</tr>
<tr>
<td>DR</td>
<td>Diameter of regenerator, cm</td>
</tr>
<tr>
<td>IC</td>
<td>ID of cooler tubes, cm</td>
</tr>
<tr>
<td>OC</td>
<td>OD of cooler tubes, cm</td>
</tr>
<tr>
<td>DW</td>
<td>Diameter of &quot;wire&quot; in regenerators</td>
</tr>
<tr>
<td>DD</td>
<td>Diameter of piston Drive Rod, cm</td>
</tr>
<tr>
<td>IH</td>
<td>ID of Heater Tubes, cm</td>
</tr>
<tr>
<td>OH</td>
<td>Heater Tube OD, cm</td>
</tr>
<tr>
<td>G</td>
<td>Gap in hot cap, cm = 0.56 cm</td>
</tr>
<tr>
<td>LB</td>
<td>Length of Hot Cap, cm</td>
</tr>
<tr>
<td>LR</td>
<td>Length of Regenerator, cm</td>
</tr>
<tr>
<td>CR</td>
<td>Length of Connecting Rod, cm</td>
</tr>
<tr>
<td>RC</td>
<td>Crank Radius, cm</td>
</tr>
<tr>
<td>LC</td>
<td>Length of cooler Tube, cm</td>
</tr>
<tr>
<td>LD</td>
<td>Heat Transfer Length of Cooler Tube, cm</td>
</tr>
<tr>
<td>LH</td>
<td>Heater Tube Length, cm</td>
</tr>
<tr>
<td>LI</td>
<td>Heater Tube Heat Transfer Length, cm</td>
</tr>
<tr>
<td>NC</td>
<td>Number of Cooler Tubes per Cylinder</td>
</tr>
<tr>
<td>NR</td>
<td>Number of Regenerators per cylinder</td>
</tr>
<tr>
<td>N</td>
<td>Number of Cylinders per Engine</td>
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<td>NH</td>
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<td>Symbol</td>
<td>Meaning and units</td>
</tr>
<tr>
<td>--------</td>
<td>-------------------</td>
</tr>
<tr>
<td>FF</td>
<td>Filler factor, fraction of regenerator volume filled with solid</td>
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<tr>
<td>AL</td>
<td>Phase Angle Alpha = 90 degrees</td>
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<tr>
<td>CX</td>
<td>Cold dead volume outside cooler Tubes, cm³ (determined by other input only)</td>
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<tr>
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<td>Mechanical Efficiency, %</td>
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<tr>
<td>FE</td>
<td>Furnace Efficiency, %</td>
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<tr>
<td>EC</td>
<td>Piston End Clearance, cm</td>
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<td>SC</td>
<td>Wall Thickness of Hot Cap, cm</td>
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<td>SE</td>
<td>Wall Thickness of Expansion Cylinder Wall, cm</td>
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<tr>
<td>SR</td>
<td>Wall Thickness of Regenerator Housing, cm</td>
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<tr>
<td>KM</td>
<td>Metal Thermal Conductivity, w/cm K</td>
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<tr>
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<td>Inside Diameter of Connecting Duct, cm</td>
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<tr>
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<td>Number of Connecting Ducts per Cylinder</td>
</tr>
<tr>
<td>BF</td>
<td>Bugger Factor to Convert Power Outputs to Nearly What GM Says They Should Be</td>
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Input and Output Printouts

ISOThERMAL SECOND ORDER CALCULATION--
PROG. ISO
09 APR 1988
WRITTEN BY WILLIAM R. MARTINI

CURRENT OPERATING CONDITIONS ARE:
SP = 200.00 PS = 200.00 ND = 30.00 TF = 1200.00
L1 = 0.0000 TV = 135.0000 FX = 25.0000 OG = 1

CURRENT DIMENSIONS ARE:
DC = 10.1680 DR = 3.5000 IC = .1150 OC = 1670
DW = .00432 DD = 4.0600 IH = .4720 OH = 6400
G = .04060 LB = 6.4000 LR = 2.5000 CR = 13.6500
RC = 2.3250 LC = 12.9000 LD = 12.8700 LH = 41.8000
LI = 25.5000 NC = 312 NR = 6 N = 4
NH = 36 FF = 2000 AL = 90.00 CX = 254.2804
ME = 90.0000 FE = 80.0000 EC = 04060 SC = .06350
SE = .10160 SR = .05100 ZZ = 1 ZH = 216.37
KM = .2000 ID = .7600 LE = 71.0000 NE = 6
BF = 4000 BB=

POWER, WATTS
BASIC 1469.2197 BASIC 2438.5757
HEATER F. L. 9384 REHEAT 47.4414
REGEN. F. L. 7430 SHUTTLE 2056.8794
COOLER F. L. 8388 PUMPING 12134
NET 1468.0123 TEMP SWING 41.6411
MECH FRIC. 146.0013 CONDUCTION 216.3688
BRAKE 1314.0111 FLOW FRIC CREDIT -4.6535
-------------------- HEAT TO ENGINE 4797.4658
INDICATED EFF % = 38.4330 FURNACE LOSS 1199.665
OVERALL EFF % = 21.9117 FUEL INPUT 5996.8320
--------------------
HOT METAL TEMP K = 922.2222 COOLING WATER INLET TEMP K = 330.5555
EFFEC HOT SP TEMP K = 876.3427 EFFEC COLD SP TEMP K = 348.5838
## Input and Output Printouts

**ISOTHERMAL SECOND ORDER CALCULATION—**  
PROG. ISO  
09 APR 1980  
WRITTEN BY WILLIAM R. MARTINI

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<th>LH</th>
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<th>NE</th>
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<tbody>
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<td>7600</td>
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<th>BB</th>
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**POWER, WATTS**

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<th>REGENERATE F.L</th>
<th>COOLER F.L</th>
<th>NET</th>
<th>MECH FRIC</th>
<th>BRAKE</th>
<th>HEAT TO ENGINE</th>
<th>FURNACE LOSS</th>
<th>FUEL INPUT</th>
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<tbody>
<tr>
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<td>1.3490</td>
<td>8.3425</td>
<td>1.3411</td>
<td>3519.5852</td>
<td>351.9586</td>
<td>3167.6267</td>
<td>6026.9458</td>
<td>128.7603</td>
<td>1948.9211</td>
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**HEAT REQUIREMENT, WATTS**

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<th>COOLER F.L</th>
<th>NET</th>
<th>MECH FRIC</th>
<th>BRAKE</th>
<th>HEAT TO ENGINE</th>
<th>FURNACE LOSS</th>
<th>FUEL INPUT</th>
</tr>
</thead>
<tbody>
<tr>
<td>3530.6177</td>
<td>1.3490</td>
<td>8.3425</td>
<td>1.3411</td>
<td>3519.5852</td>
<td>351.9586</td>
<td>3167.6267</td>
<td>6026.9458</td>
<td>128.7603</td>
<td>1948.9211</td>
</tr>
</tbody>
</table>

**HOT METAL TEMP K = 922.2222**  
**COOLING WATER INLET TEMP, K = 330.5555**  
**EFFEC HOT SP TEMP K = 853.7864**  
**EFFEC COLD SP TEMP, K = 353.9690**
Table B.1 (continued)

Input and Output Printouts

<table>
<thead>
<tr>
<th>FROM</th>
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<th>VALUE</th>
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CURRENT OPERATING CONDITIONS ARE:
SP = 200.00  PS = 1000.00  ND = 30.00  TF = 1200.00
L1 = 0.0000  TV = 135.0000  FX = 25.0000  OG = 1

CURRENT DIMENSIONS ARE:
DC = 10.1600  DR = 3.5000  IC = 1.1500  OC = .1670
DN = 0.00432  DD = 4.0600  IH = .4720  OH = 6400
C = .04060  LB = 6.4800  LR = 2.5000  CR = 13.6500
RC = 2.3250  LC = 12.9000  LD = 12.0200  LH = 41.0000
LI = 25.5800  NC = 312  NR = 6  N = 4
NH = 36  FF = .2000  AL = 90.00  CX = 254.2804
ME = 90.0000  FE = 80.0000  EC = .04060  SC = .06350
SE = 1.0810  SR = .05100  ZZ = 1  LH = 185.61
KM = .2000  ID = .7600  LE = 71.0000  NE = 6
BF = .4000  BB =

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**Table B.1 (continued)**

**Input and Output Printouts**

**ISOTHERMAL SECOND ORDER CALCULATION--**

PROC ISO
09 APR 1988

WRITTEN BY WILLIAM R. MARTINI

**CURRENT OPERATING CONDITIONS ARE:**

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**CURRENT DIMENSIONS ARE**

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**POWER. WATTS**

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<td>SHUTTLE</td>
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<tr>
<td>FUEL INPUT</td>
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**HOT METAL TEMP. K = 922.2222 | COOLING WATER INLET TEMP., K = 338.5555**

**EFFEC HOT SP. TEMP. K = 798.3881 | EFFEC COLD SP. TEMP. K = 368.2829**

155
**Input and Output Printouts**

**ISOTHERMAL SECOND ORDER CALCULATION--**

**PROG. ISO**
09 APR 1988
**WRITTEN BY WILLIAM R. MARTINI**

**CURRENT OPERATING CONDITIONS ARE:**

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<td>.6400</td>
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<td>LR</td>
<td>2.5000</td>
<td>CR</td>
<td>13.6500</td>
</tr>
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<td>12.0200</td>
<td>LH</td>
<td>41.8000</td>
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<tr>
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<td>25.5000</td>
<td>NC</td>
<td>312</td>
<td>NR</td>
<td>6</td>
<td>N</td>
<td>4</td>
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<tr>
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<td>FF</td>
<td>2000</td>
<td>AL</td>
<td>90.00</td>
<td>CX</td>
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<td>FE</td>
<td>80.0000</td>
<td>EC</td>
<td>.04060</td>
<td>SC</td>
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<td>ZH</td>
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**POWER, WATTS**

| BASIC      | 3541.0500 | BASIC          | 6032.8877 |
| HEATER F L | 8.4157    | REHEAT         | 121.0556  |
| REGEN F L  | 52.0297   | SHUTTLE        | 1955.5525 |
| COOLER F L | 8.3694    | PUMPING        | 51772.0   |
| NET        | 3472.2361 | TEMP SWING     | 101.3289  |
| MECH FRIC  | 347.2237  | CONDUCTION     | 205.7099  |
| BRAKE      | 3125.0125 | FLOW FRIC.CREDIT| -34.4306 |
|**HEAT TO ENGINE** |         |                 | 8387.2803 |
|**INDICATED EFF %** | 41.3988 | **FURNACE LOSS** | 2096.8198 |
|**OVERALL EFF %**  | 29.0072  | **FUEL INPUT**  | 18484.0996|

---

| HOT METAL TEMP K | 922.2222 | COOLING WATER INLET TEMP K | 330.5555 |
| EFFEC HOT SP TEMP K | 854.9666 | EFFEC COLD SP TEMP K | 353.4785 |
**Table B.1 (continued)**

**Input and Output Printout**

**Isothermal Second Order Calculation—**

**PROG. ISO**

09 APR 1989

**Written by William R. Martini**

**Current Operating Conditions Are:**

- SP = 500.00
- PS = 500.00
- ND = 30.06
- TF = 1200.00
- L1 = 0.0000
- TV = 135.0000
- FX = 25.0000
- DG = 1

**Current Dimensions Are:**

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<thead>
<tr>
<th>DC</th>
<th>10.1600</th>
<th>DR</th>
<th>3.5000</th>
<th>IC</th>
<th>.1150</th>
<th>OC</th>
<th>.1670</th>
</tr>
</thead>
<tbody>
<tr>
<td>DW</td>
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<td>DD</td>
<td>4.0600</td>
<td>IH</td>
<td>.4720</td>
<td>OH</td>
<td>.6400</td>
</tr>
<tr>
<td>G</td>
<td>.04060</td>
<td>LB</td>
<td>6.4000</td>
<td>LR</td>
<td>2.5000</td>
<td>CR</td>
<td>13.6500</td>
</tr>
<tr>
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<td>2.3250</td>
<td>LC</td>
<td>12.9000</td>
<td>LD</td>
<td>12.6200</td>
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<td>25.5000</td>
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<td>NN</td>
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<td>FF</td>
<td>.2800</td>
<td>AL</td>
<td>90.00</td>
<td>CX</td>
<td>254.2804</td>
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<tr>
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<td>80.0000</td>
<td>EC</td>
<td>.8400</td>
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<td>.06350</td>
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<td>.05100</td>
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<tr>
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<td>DB</td>
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**Power, Watts**

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<thead>
<tr>
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<th>7999.3381</th>
<th>BASIC</th>
<th>14640.6825</th>
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</thead>
<tbody>
<tr>
<td>HEATER F. L.</td>
<td>18.7768</td>
<td>REHEAT</td>
<td>292.8714</td>
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<tr>
<td>REGEN. F. L.</td>
<td>66.9300</td>
<td>SHUTTLE.</td>
<td>1714.6409</td>
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<td>COOLER F. L.</td>
<td>18.5975</td>
<td>PUMPING</td>
<td>21.4229</td>
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<tr>
<td>NET</td>
<td>7894.6260</td>
<td>TEMP. SWING</td>
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<td>MECH. FRIC.</td>
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<td>CONDUCTION</td>
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<td>BRAKE</td>
<td>7185.1636</td>
<td>FLOW FRIC. CREDIT</td>
<td>-52.2418</td>
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**Heat Requirement, Watts**

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<thead>
<tr>
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<tr>
<td>INDICATED EFF. %</td>
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<tr>
<td>FURNACE LOSS</td>
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<tr>
<td>OVERALL EFF. %</td>
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<tr>
<td>FUEL INPUT</td>
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</tbody>
</table>

**HOT METAL TEMP. K =** 922.2222  **COOLING WATER INLET TEMP. K =** 330.5555  **EFFECTIVE HOT SP. TEMP. K =** 806.0047  **EFFEC. COLD SP. TEMP. K =** 363.5899
Table B.1 (continued)

Input and Output Printouts

ISOTHERMAL SECOND ORDER CALCULATION--
PROG. ISO
09 APR 1980
WRITTEN BY WILLIAM R. MARTINI

CURRENT OPERATING CONDITIONS ARE:
SP= 500.00 PS= 1000.00 ND= 30.00 TF= 1200.00
LI= 0.0000 TV= 135.0000 FX= 25.0000 OG= 1

CURRENT DIMENSIONS ARE:
DC= 10.1600 DR= 3.5000 IC= .1150 OC= 1.670
DH= .00432 DO= 4.0600 IH= .4720 OH= .6400
G= .04060 LB= 6.4000 LR= 2.5000 CR= 13.6500
RC= 2.3250 LC= 12.9000 LD= 12.0200 LH= 41.8000
LI= 25.5000 NE= 312 NR= 6 N= 4
NH= 36 FF=.2000 AL=.90.00 CX= 254.2804
ME= 90.0000 FE=.80.0000 EC=.04060 SC=.06350
SE= 10168 SR=.05180 ZZ= 1 ZH= 195.95
KM=.2000 ID=.7600 LE=.71.0000 NE= 6
BF=.4000 BB=

POWER, WATTS HEAT REQUIREMENT, WATTS
BASIC 17191.9375 BASIC 29910.8047
HEATER F. L. 34.2715 REHEAT 641.8933
REGEN. F. L. 85.3313 SHUTTLE 1862.7869
COOLER F. L. 34.9928 PUMPING 66.6066
NET 17037.3437 TEMP. SWING 2475.5483
MECH. FRIC. 1703.7346 CONDUCTION 195.9516
BRAKE 15333.6094 FLOW FRIC CREDIT -76.9372
---------------------------------- HEAT TO ENGINE 35076.6523
INDICATED EFF. % 48.5717 FURNACE LOSS 8769.1621
OVERALL EFF. % 34.9717 FUEL INPUT 43845.8125

----------------------------------
HOT METAL TEMP. K= 922.2222 COOLING WATER INLET TEMP. K= 330.5555
EFFEC. HOT SP. TEMP K= 832.8246 EFFEC. COLD SP. TEMP. K = 353.8192

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Input and Output Printouts

Isothermal Second Order Calculation--

PROG. ISO
09 APR 1986

Written by William R. Martini

Current Operating Conditions Are:

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<th>TF</th>
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</thead>
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Current Dimensions Are:

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Power, Watts

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<td>SHUTTLE</td>
<td>1911.5562</td>
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<td>46.5041</td>
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<tr>
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<td>COUCTION</td>
<td>201.8618</td>
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Heat Requirement, Watts

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<td>REHEAT</td>
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<tr>
<td>REGEN. F. L.</td>
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<td>SHUTTLE</td>
<td>1911.5562</td>
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<tr>
<td>COOLER F. L.</td>
<td>46.5041</td>
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<td>NET</td>
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<td>MECH. FRIC.</td>
<td>2425</td>
<td>COUCTION</td>
<td>201.8618</td>
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<td>BRAKE</td>
<td>21831</td>
<td>6113</td>
<td>FLOW FRIC. CREDIT</td>
</tr>
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---------------------------------

Indicated Eff. % = 48.4612

Fuel Input = 62569.8312

Overall Eff. % = 34.8512

---------------------------------

Hot Metal Temp. K = 922.2222

Cooling Water Inlet Temp. K = 330.5555

Effec. Hot SP. Temp. K = 844.6619

Effec. Cold SP. Temp. K = 353.6819
Table B.1 (continued)

Input and Output Printout

ISOThermal Second Order Calculation—
PROG. ISO
09 APR 1988
WRITTEN BY WILLIAM R. MARTINI

CURRENT OPERATING CONDITIONS ARE:
SP = 1500 00
ND = 20 00
TF = 1200 00

INPUT AND OUTPUT PRINTOUT

CURRENT DIMENSIONS ARE:

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<th>OC</th>
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<th>OH</th>
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<th>LR</th>
<th>CR</th>
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<th>N</th>
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<table>
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<td>.710000</td>
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</tbody>
</table>

<table>
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<th>BB</th>
</tr>
</thead>
<tbody>
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</table>

POWER, WATTS

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</thead>
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<td>237.8720</td>
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<tr>
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<td>-181.7791</td>
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<table>
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<tr>
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<th>FUEL INPUT</th>
</tr>
</thead>
<tbody>
<tr>
<td>60.7231</td>
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</tbody>
</table>

| INDICATED EFF | 44.4038 |
| OVERALL EFF | 31.9707 |

| HOT METAL TEMP. | 922.2222 |
| EFFECTIVE HOT SP TEMP. | 823.6807 |
| EFFECTIVE COLD SP TEMP. | 362.7874 |

| K  | 922.2222 |
| K  | 330.5555 |
| K  | 362.7874 |
### Table B.1 (continued)

**Input and Output Printouts**

**ISOTHERMAL SECOND ORDER CALCULATION---**

**PROG ISO**

09 APR 1980

**WRITTEN BY WILLIAM R. MARTINI**

**CURRENT OPERATING CONDITIONS ARE:**

<table>
<thead>
<tr>
<th>SP</th>
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<th>ND</th>
<th>TF</th>
</tr>
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<td>1000</td>
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</tbody>
</table>

<table>
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<th>TV</th>
<th>FX</th>
<th>OG</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.000</td>
<td>135.000</td>
<td>25.000</td>
<td>1</td>
</tr>
</tbody>
</table>

**CURRENT DIMENSIONS ARE**

<table>
<thead>
<tr>
<th>DC</th>
<th>DR</th>
<th>IC</th>
<th>OC</th>
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</thead>
<tbody>
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<table>
<thead>
<tr>
<th>DM</th>
<th>DD</th>
<th>IH</th>
<th>OH</th>
</tr>
</thead>
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**POWER, WATTS**

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<td>REHEAT</td>
<td>646 2640</td>
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<td>REGEN F L</td>
<td>339 8281</td>
<td>SHUTTLE</td>
<td>1881 3140</td>
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<tr>
<td>COOLER F L</td>
<td>129 5549</td>
<td>PUMPING</td>
<td>66 8533</td>
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<td>NET</td>
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<td>1245 6926</td>
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<td>MECH FRIC</td>
<td>1672 0549</td>
<td>CONDUCTION</td>
<td>197 9086</td>
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<tr>
<td>BF*E</td>
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<td>FLOW FRIC CREDIT</td>
<td>-306 3230</td>
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**HEAT REQUIREMENT, WATTS**

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<td>HEATER F L</td>
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<tr>
<td>REGEN F L</td>
<td>1881 3140</td>
</tr>
<tr>
<td>COOLER F L</td>
<td>66 8533</td>
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<tr>
<td>NET</td>
<td>1245 6926</td>
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<tr>
<td>MECH FRIC</td>
<td>197 9086</td>
</tr>
<tr>
<td>BF*E</td>
<td>-306 3230</td>
</tr>
</tbody>
</table>

**INDICATED EFF $$= 49 5867$$**

<table>
<thead>
<tr>
<th>FURNACE LOSS</th>
<th>8429 8496</th>
</tr>
</thead>
<tbody>
<tr>
<td>OVERALL EFF $$= 35 7024$$</td>
<td>42149 2422</td>
</tr>
</tbody>
</table>

**HOT METAL TEMP $$= 922 2222$$**

| COOLING WATER INLET TEMP , $$K = 330.5555$$ |
| EFFE\* HOT SP TEMP $$K = 856 1503$$ | EFFE\* COLD SP TEMP $$K = 352 5077$$ |
### Table B.1 (continued)

**Input and Output Printouts**

**ISOTHERMAL SECOND ORDER CALCULATION**

**PROG. ISO**

09 APR 1988

**WRITTEN BY WILLIAM R. MARTINI**

**CURRENT OPERATING CONDITIONS ARE:**

<table>
<thead>
<tr>
<th>SP</th>
<th>1000.00</th>
<th>PS</th>
<th>1000.00</th>
<th>ND</th>
<th>30.00</th>
<th>TF</th>
<th>1200.00</th>
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</thead>
<tbody>
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<td>FX</td>
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**CURRENT DIMENSIONS ARE:**

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<th>IC</th>
<th>.1150</th>
<th>OC</th>
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<tr>
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<td>LB</td>
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<td>LR</td>
<td>2.5000</td>
<td>CR</td>
<td>13.6500</td>
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<tr>
<td>RC=</td>
<td>2.3250</td>
<td>LC</td>
<td>12.9000</td>
<td>LD</td>
<td>12.0200</td>
<td>LH</td>
<td>41.8000</td>
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<tr>
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<td>NC</td>
<td>312</td>
<td>NR</td>
<td>6</td>
<td>N</td>
<td>4</td>
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<td>.2000</td>
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<td>CX</td>
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<td>FC</td>
<td>.00000</td>
<td>SC</td>
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<td>.05100</td>
<td>ZZ</td>
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<td></td>
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<tr>
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**POWER, WATTS**

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>BASIC</td>
<td>60104.5156</td>
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<td></td>
<td>1364.5734</td>
<td>SHUTTLE</td>
</tr>
<tr>
<td></td>
<td>5037.6309</td>
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<td></td>
<td>201.6665</td>
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<tr>
<td></td>
<td>-493.4098</td>
<td></td>
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</table>

**INDICATED EFF. %** = 49.6997

**OVERALL EFF. %** = 35.7838

**HOT METAL TEMP. K** = 922.2222

**EFFEC. HOT SP. TEMP. K** = 845.7885

<table>
<thead>
<tr>
<th>HOT METAL TEMP. K = 922.2222</th>
<th>COOLING WATER INLET TEMP., K = 330.5555</th>
</tr>
</thead>
<tbody>
<tr>
<td>EFFEC. HOT SP. TEMP. K = 845.7885</td>
<td>EFFEC. COLD SP. TEMP. K = 354.2686</td>
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</tbody>
</table>

162
Table B.1 (continued)

**Inputs and Output Printouts**

**Isothermal Second Order Calculation**

**PROG. ISO**

09 Apr 1980

**Written by William R. Martini**

**Current Operating Conditions Are:**

<table>
<thead>
<tr>
<th>SP</th>
<th>1000.00</th>
<th>PS</th>
<th>1400.00</th>
<th>ND</th>
<th>30.00</th>
<th>TF</th>
<th>1200.00</th>
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**Current Dimensions Are:**

<table>
<thead>
<tr>
<th>DC</th>
<th>10.1600</th>
<th>DR</th>
<th>3.5000</th>
<th>IC</th>
<th>.1150</th>
<th>OC</th>
<th>.1670</th>
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**Power, Watts**

<table>
<thead>
<tr>
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<th>47958.7500</th>
<th>HEATER F. L.</th>
<th>345.9294</th>
<th>REGENERATION F. L.</th>
<th>66.7500</th>
<th>COOLER F. L.</th>
<th>350.3559</th>
<th>NET</th>
<th>46655.1758</th>
<th>MECH FRICTION</th>
<th>4665.5186</th>
<th>BRAKE</th>
<th>41989.6602</th>
<th>HEAT TO ENGINE</th>
<th>97052.1875</th>
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<tbody>
<tr>
<td>83615.6094</td>
<td>1920.1581</td>
<td>1875.4663</td>
<td>343.8532</td>
<td>9749.3984</td>
<td>197.2854</td>
<td>-649.5749</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Indicated Eff % = 46.0723**

**Overall Eff % = 34.6120**

**Hot Metal Temp. K = 922.2222**

**Cooling Water Inlet Temp. K = 338.5555**

**Effec. Hot SP. Temp. K = 838.6689**

**Effec. Cold SP. Temp. K = 358.1397**
Table B.1 (continued)

Input and Output Printouts

ISOETHERMAL SECOND ORDER CALCULATION--
PROG. ISO
09 APR 1988
WRITTEN BY WILLIAM R. MARTINI

CURRENT OPERATING CONDITIONS ARE:
SP = 2000.00 PS = 200.00 ND = 30.00 TF = 1200.00
L1 = 0.0000 TY = 135.0000 FX = 25.0000 OG = 1

CURRENT DIMENSIONS ARE:
DC = 10.1600 DR = 3.5000 IC = 0.1150 OC = 0.1670
DW = 0.00432 DD = 4.0600 IH = 0.4720 OH = 0.6400
G = 0.0468 LB = 6.4000 LR = 2.5000 CR = 13.6500
RC = 2.2250 LC = 12.9000 LD = 12.0200 LH = 41.8000
L1 = 25.5000 NC = 312 NR = 6 N = 4
NH = 36 FF = 0.2000 AL = 90.00 CX = 254.2004
ME = 90.0000 FE = 80.0000 EC = 0.04060 SC = 0.06350
SE = 0.10100 SR = 0.05100 Z2 = 1 ZH = 191.16
KM = 0.2000 ID = 0.7600 LE = 71.0000 NE = 6
BF = 0.4000 BB =

POWER, WATTS

BASIC 13460.6621 BASIC 23766.1650
HEATER F. L. 451.8111 REHEAT 498.5541
REGEN F. L. 1244.8168 SHUTTLE 1817.2532
COOLER F. L. 458.8861 PUMPING 46.2341
NET 11306.7461 TEMP SWING 398.0685
MECH. FRIC. 1130.6748 CONDUCTION 191.1619
BRAKE 10176.8713 FLOW FRIC. CREDIT -1073.0195

---------------------------------- HEAT TO ENGINE 25625.4160

INDICATED EFF. % = 44.1059 FURNACE LOSS 6408.8525
OVERALL EFF. % = 31.7563 FUEL INPUT 32044.2656

----------------------------------

HOT METAL TEMP. K = 922.2222 COOLING WATER INLET TEMP. K = 330.5555
EFFEC HOT SP. TEMP. K = 824.1782 EFFEC. COLD SP TEMP. K = 357.3217

--------------
Table B.1 (continued)

Input and Output Printcuts

ISOTHERMAL SECOND ORDER CALCULATION--
PROG. ISO
09 APR 1980
WRITTEN BY WILLIAM R. MARTINI

CURRENT OPERATING CONDITIONS ARE:
SP= 2000.00 PS= 500.00 ND= 30.00 TF= 1200.00
L1= 0.0000 TY= 135.0000 FX= 25.0000 OG= 1

CURRENT DIMENSIONS ARE:
DC= 10.1600 DR= 3.5000 IC= .1150 OC= .1670
DW= .00432 DD= 4.0600 IH= .4720 OH= .6400
G= .04060 LB= 6.4000 LR= 2.5000 CR= 13.6500
RC= 2.3250 LC= 12.9000 LD= 12.0200 LH= 41.8000
LI= 25.5000 NC= 312 NR= 6 N= 4
NH= .06 FF= 2000 AL= 90.00 CX= 254.2884
ME= 90.0000 FE= 80.0000 EC= .04060 SC= .06350
SE= .10160 SR=.05100 ZZ= 1 ZH= 203.62
KM= .2000 ID= .7600 LE= 71.0000 NE= 6
BF= 4000 BB=

POWER, WATTS

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<td>SHUTTLE</td>
<td>1935.7202</td>
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<td>COOLER F L</td>
<td>1019.1125</td>
<td>PUMPING</td>
<td>203.8463</td>
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<td>NET</td>
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<td>TEMP SWING</td>
<td>2532.4609</td>
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<td>MECH FRIC.</td>
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<td>CONDUCTION</td>
<td>203.6237</td>
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<td>BRAKE</td>
<td>28136.0156</td>
<td>FLOW FRIC CREDIT</td>
<td>-1959.5837</td>
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</table>

| INDICATED EFF. % | 48.4522 |
| FURNACE LOSS | 16310.4551 |
| OVERALL EFF. % | 34.8156 |
| FUEL INPUT | 80652.2734 |

| HOT METAL TEMP K | 922.2222 |
| COOLING WATER INLET TEMP. K | 330.5555 |
| EFFEC HOT SP TEMP K | 849.8555 |
| EFFEC COLD SP TEMP K | 353.4494 |
Table B.1 (continued)

Input and Output Printouts

**ISOTHERMAL SECOND ORDER CALCULATION**
PROG. ISO
09 APR 1980
WRITTEN BY WILLIAM R. MARTINI

CURRENT OPERATING CONDITIONS ARE:
SP = 2000.00  PS = 1000.00  ND = 30.00  TF = 1200.00
L1 = 0.0000  TV = 135.0000  FX = 250000  OG = 1

CURRENT DIMENSIONS ARE:
DC = 10.1600  DR = 3.5000  IC = .1150  OC = .1670
DW = .00432  DD = 4.0600  IH = .4720  OM = .6400
G = .04060  LB = 6.4000  LR = 2.5000  CR = 13.5000
RC = 2.3250  LC = 12.9000  LD = 12.0200  LH = 41.0000
LI = 25.5000  NC = 312  NR = 6  N = 4
NH = .36  FF = .2000  AL = .90 00  CX = 254.2804
ME = 90.0000  FE = 80.0000  EC = .84068  SC = .06350
SE = .10160  SR = .05100  ZZ = 1  ZH = 194.83
KM = .2000  ID = .7600  LE = 71.0000  NE = 6
BF = 4000  BB =

POWER, WATTS  HEAT REQUIREMENT, WATTS
BASIC  67612 1816  BASIC  118928.5312
HEATER F. L.  1927.4056  REHEAT  2778.0645
REGEN. F. L.  3147.8110  SHUTTLE  1852.1472
COOLER F. L.  1946.4116  PUMPING  602.3567
NET  60590.3984  TEMP. SWING  9880.2656
MECH FRIC.  6059.0410  CONDUCTION  194.8324
BRAKE  54531.3594  FLOW FRIC CREDIT -3581.3911
---------------------------------- HEAT TO ENGINE  120754.7959
INDICATED EFF. %= 46.3460  FURNACE LOSS  32683.6992
OVERALL EFF. %= 33.3691  FUEL INPUT  163418.4844
----------------------------------
HOT METAL TEMP. K = 922.2222  COOLING WATER INLET TEMP. K = 330.5555
EFFEC HOT SP. TEMP. K = 836.6948  EFFEC COLD SP. TEMP. K = 360.9674
Table B.1 (continued)

Input and Output Printouts

ISOThERMAL SECOND ORDER CALCULATION--
PROG. ISO
09 APR 1980
WRITTEN BY WILLIAM R. MARTINI

CURRENT OPERATING CONDITIONS ARE:
SP = 2000.00 PS = 1400.00 ND = 30.00 TF = 1200.00
L1 = 0.0000 TY = 155.0000 FX = 25.0000 OG = 1

CURRENT DIMENSIONS ARE:
DC = 10.1600 DR = 2.5000 IC = .1150 OC = 1670
DW = 004324 DD = 4.0600 IH = .4720 OH = 6400
G = 04060 LB = 6.4000 LR = 2.5000 CR = 13.6500
PC = 2.2250 LC = 12.9000 LD = 12.0200 LH = 41.8000
LI = 25.5800 MC = 312 NR = 6 N = 4
NH = 26 FF = 2000 AL = 90.00 CX = 254.2804
ME = 90.0000 FE = 80.0000 EC = .04060 SC = .06350
SE = 10160 SR = .05100 ZZ = 1 ZH = 186.94
HM = 2000 ID = .7600 LE = 71.0000 NE = 6
BF = 4000

POWER, WATTS

<table>
<thead>
<tr>
<th>HEAT REQUIREMENT, WATTS</th>
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</thead>
<tbody>
<tr>
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<tr>
<td>HEATER F L 2651.8196</td>
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<tr>
<td>REGEN F. L 4117.2451</td>
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<tr>
<td>COOLER F L 2677.4727</td>
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<tr>
<td>NET 8241.3594</td>
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<tr>
<td>MECH FRIC 8241.5371</td>
</tr>
<tr>
<td>BRAKE 74173.8281</td>
</tr>
</tbody>
</table>

| INDIcATED EFF. % = 44.2429 | FURNACE LOSS 46569.8437 |
| OVERALL EFF. % = 31.8549       | FUEL INPUT 232849.2187 |

| HOT METAL TEMP k = 922.2222 | COOLING WATER INLET TEMP., k = 330.5555 |
| EFFEC HOT SP TEMP k = 828.4016 | EFFEC COLD SP. TEMP. k = 366.9746 |
The first step was to plot the minimum flow loss versus the speed squared. This plot is shown in Figure B.2. This relationship is linear and was easily fitted. This relationship allowed prediction of flow loss at relatively high pressures. The final step was to develop the correlation that would allow predictions at relatively low pressures. The change in the torque ratio between the highest value (high pressure) and the values at other pressures is shown in Figure B.3. In one attempt to bring the curves together, it was decided to divide the change by the speed. An average of these curves was fitted with a power curve. The curves are shown in Figure B.4. Taking into account both effects, the final equation was:

\[ TQN = TQI \times (0.99862 - 9.14 \times 10^{-5} (SP)^2) (1 - 3.09 \times 10^{-3} (SP)(MPa)^{-1.841}) \]

where \( TQN \) is net torque, \( TQI \) is indicated torque, \( SP \) is engine speed in Hertz, and \( MPa \) is engine pressure in MPa.

Validation of this equation consisted in using it to calculate a torque ratio for the 16 cases previously calculated.

The predictions were compared with the calculated results and plotted in Figure B.5. The error band fits were within the error expected from the actual fluid mechanic calculations. This method of estimating flow loss is reasonably accurate and saves computer time and space.

![Figure B.2. Minimum Flow Loss Versus Speed Squared.](image-url)
Figure B.3. Maximum Torque Ratio Change Versus Pressure.

Figure B.4. Torque Curve Correlation.
Figure B.5. Predictions Versus Actual Calculations.
APPENDIX C

GRAPHIC SUBROUTINES

The graphic subroutines listed and explained in this appendix were left out of the listing of CNTLB.FOR because they had already been included in the library for the Altos computer at Martini Engineering. Other computers will probably have different graphic packages, so an explanation of what each subroutine does is included. The subroutines are VECTOR, POINT and CLEAR. Also, an explanation of the subroutine ERASE given on lines 888 to 922 of CNTLB (see page 104) will be given. All of these use a machine language subroutine CONOUT. (See Table C.1 for a listing of CONOUT.) The Retrographics* modification to the Lear-Siegler AIM-3A terminal employs certain control codes to get between the different modes. This control chart is shown in Figure C.1. CONOUT is used to give the computer the signal in

Table C.1

MACHINE LANGUAGE LISTING OF CONOUT

<table>
<thead>
<tr>
<th>ENTRY</th>
<th>CONOUT</th>
</tr>
</thead>
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<td>00001100B</td>
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<td>CONOUT</td>
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<td>1CH</td>
</tr>
<tr>
<td>RET</td>
<td>END</td>
</tr>
</tbody>
</table>

Figure C.1. Retrographics Control Scheme.

the proper form to be recognized. Table C.2 shows the code that is used. The subroutines will now be explained.

Table C.2
CONTROL CODES

<table>
<thead>
<tr>
<th>ASCII Code Name</th>
<th>Name in Subroutine</th>
<th>ASCII Decimal Number</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAN</td>
<td>CA</td>
<td>24</td>
<td>Move from 4010 alpha to ADM-3A alpha.</td>
</tr>
<tr>
<td>EM</td>
<td>UY</td>
<td>25</td>
<td>Clear screen.</td>
</tr>
<tr>
<td>FS</td>
<td>FS</td>
<td>28</td>
<td>Move to point mode.</td>
</tr>
<tr>
<td>GS</td>
<td>GS</td>
<td>29</td>
<td>Move to vector mode.</td>
</tr>
<tr>
<td>US</td>
<td>US</td>
<td>31</td>
<td>Move from vector mode to 4010 alpha.</td>
</tr>
<tr>
<td>ESC</td>
<td>ES</td>
<td>27</td>
<td>Sets data level to black</td>
</tr>
<tr>
<td>DEL</td>
<td>DE</td>
<td>127</td>
<td>With ES sets data level to white.</td>
</tr>
<tr>
<td>a</td>
<td>AA</td>
<td>97</td>
<td></td>
</tr>
</tbody>
</table>

VECTOR

The subroutine VECTOR draws a straight line. It is listed in Table C.3. It has four arguments. They are defined as follows:

\[
\begin{align*}
JX &= X \text{ axis coordinate of start of vector.} \\
JY &= Y \text{ axis coordinate of start of vector.} \\
KX &= X \text{ axis coordinate of end of vector.} \\
KY &= Y \text{ axis coordinate of end of vector.}
\end{align*}
\]

As for any subroutine, the position is important and the names can be changed. These coordinates are integers. The main program scales the values to be plotted so that the X axis coordinate is between 0 and 1023 and the Y axis coordinate is between 0 and 779. (See Figure C.2.)

In line 757 of Table C.3 the integers are defined. In line 758 the values needed from Table C.2 are defined. In line 759 the control code GS is sent to go from the ADM-3A alpha mode to the vector mode (see Figure C.1). In lines 760 and 761 the Y coordinate of the start of the vector is split into its upper and lower components according to directions. In lines 762 and 763 the same thing is done for the X coordinate of the start of the vector. In lines 764 to 767 these four numbers are entered. Lines 768-770 cause a slight delay in the program to allow the entering to be complete.

From lines 771 to 780 the same thing is done for the end coordinate of the vector. Once the computer has both coordinates, it draws a straight line between them. The timing loop (lines 779 to 781) is needed to allow the computer to draw the line before it goes on to something else. The time...
Table C.3

755: C SUBROUTINE FOR DRAWING A VECTOR ON THE SCREEN
756: SUBROUTINE VECTOR(JX, JY, KX, KY)
757: INTEGER*1 GS, US, YH, YL, XH, XL, CA
758: DATA GS, US, CA/29, 31, 24/
759: CALL CONOUT(GS)
760: YH=JY/32+32
761: YL=MOD(JY, 32)+96
762: XH=JX/32+32
763: XL=MOD(JX, 32)+64
764: CALL CONOUT(YH)
765: CALL CONOUT(YL)
766: CALL CONOUT(XH)
767: CALL CONOUT(XL)
768: DO 10 I=1, 200
769: N=I+1
770: 10 CONTINUE
771: YH=KY/32+32
772: YL=MOD(KY, 32)+96
773: XH=KX/32+32
774: XL=MOD(KX, 32)+64
775: CALL CONOUT(YH)
776: CALL CONOUT(YL)
777: CALL CONOUT(XH)
778: CALL CONOUT(XL)
779: DO 20 I=1, 200
780: N=I+1
781: 20 CONTINUE
782: CALL CONOUT(US)
783: CALL CONOUT(CA)
784: RETURN
785: END

Figure C.2. Coordinate Numbering for Graphics.
delay used here works for even the longest line.

Lines 782 and 783 get control back to the ADM-3A alpha mode by going through the 4010 alpha mode. (See Figure C.1 and Table C.2.)

POINT

The subroutine POINT puts a point on the screen. It is listed on Table C.4. It has two arguments:

   JP = X axis of point
   JQ = Y axis of point

Table C.4

727:  C SUBROUTINE FOR POINT GRAPHICS
728:      SUBROUTINE POINT(JP, JQ)
729:      INTEGER FS, US, CA, VH, VL, XH, XL, UV
731:      CALL CONOUT(FS)
732:      VH=JP/32+32
733:      XL=MOD(JP, 32)+64
734:      CALL CONOUT(XL)
735:      CALL CONOUT(YH)
736:      CALL CONOUT(US)
737:      CALL CONOUT(UL)
738:      CALL CONOUT(UY)
739:      CALL CONOUT(US)
740:      CALL CONOUT(UL)
741:      CALL CONOUT(UY)
742:      RETURN
743:      END

As for any subroutine the positions of the arguments are important and the names can be changed. These coordinates are integers scaled as shown in Figure C.2. In lines 729 and 730 of Table C.4 the integers and the data are defined. In line 731 the control code FS is sent to get control into the point mode. (See Figure C.1.) In lines 732 to 739 the upper and lower component of each coordinate is calculated and sent in the proper order. A point corresponding to this coordinate lights up on the screen. Lines 740 and 741 return control to the ADM-3A alpha mode via the 4010 alpha mode (see Figure C.1).

CLEAR

The subroutine CLEAR erases the entire graphic screen without touching the ADM-3A alpha screen which is superimposed. CLEAR has no arguments. A listing is shown in Table C.5. In Table C.5, lines 746 and 747 initialize as usual. In line 748 the control code GS is sent to get the control into the vector mode. In this mode sending the control code EM (UY in our subroutine) (see Table C.2) clears all the screen. Lines 750 and 751 get control back to ADM-3A alpha mode in the usual way.
The subroutine **ERASE** draws a series of black lines from X coordinate 710 to 1013. The black lines are drawn in the Y direction from 2 to 777. On page 104 lines 889 and 890 initialize things. Line 891 starts the do loop. Line 892 gets control to the vector mode. Lines 893 and 894 together set the data level to black from white. Lines 895 to 914 draw a black line. Lines 915 and 916 set the data level back to white. Lines 917 and 918 get back to the AIM-3A alpha mode. Line 919 is the end of the do loop.

An attempt was made to shorten this subroutine by putting the do loop in the vector mode part of the program, but this did not work. The subroutine requires 6 seconds to clear this part of the screen. More efficient subroutines for clearing part of the screen can probably be worked out, but this subroutine was not a vital part in the total computing time.

Graphic output greatly speeds the comprehension of the computed results. It should always be used if available for this type of analysis.