A COMMERCIAL HEATING BOILER
TRANSIENT ANALYSIS SIMULATION
MODEL (DEPAB2)

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ABSTRACT

This report documents a second generation boiler transient analysis computer program DEPAB2. DEPAB2 improves the efficiency and accuracy of calculation over the original NBS-developed boiler transient analysis program DEPAB. DEPAB2 treats in detail the boiler controllers and different modes of heat transfer (conductive, convective and radiative) which occur in commercial boilers. It is built upon seven principal subroutines for the controller and interface flux calculations and 16 auxiliary subroutines for fluid properties. fuel/air combustion and heat transfer parameters.

Also included in this report is a guide on using DEPAB2. It contains: (1) input data requirements for DEPAB2 runs, (2) procedures for DEPAB2 runs, and (3) output data interpretation.

In addition, a worked example is described and discussed in detail to illustrate: (1) the DEPAB2 runs, (2) quantitative information generated by DEPAB2, and (3) the use of information from DEPAB2 to calculate boiler efficiency and examine energy conservation control strategies.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>ii</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>iv</td>
</tr>
<tr>
<td>1. INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>2. BOILER CONTROLLER DYNAMICS AND SUBROUTINE CT</td>
<td>3</td>
</tr>
<tr>
<td>3. BOILER THERMAL DYNAMICS AND SUBROUTINES</td>
<td>7</td>
</tr>
<tr>
<td>3.1 Math Model and Subroutine SR for Gas/Furnace Heat Flux at On Period</td>
<td>10</td>
</tr>
<tr>
<td>3.2 Math Model and Subroutine LT for Gas/Tube Heat Flux at On Period</td>
<td>11</td>
</tr>
<tr>
<td>3.3 Math Model and Subroutine FG for Off Period Gas/Solid Interface Heat Transfer</td>
<td>16</td>
</tr>
<tr>
<td>3.4 Subroutine DB and SGHT for Water Side Heat Transfer</td>
<td>16</td>
</tr>
<tr>
<td>3.5 Subroutine SH for Boiler Shell Heat Loss</td>
<td>19</td>
</tr>
<tr>
<td>3.6 Auxiliary Subroutines</td>
<td>22</td>
</tr>
<tr>
<td>4. COMMERCIAL BOILER TRANSIENT ANALYSIS COMPUTER PROGRAM DEPAB2</td>
<td>26</td>
</tr>
<tr>
<td>5. USER'S GUIDE</td>
<td>33</td>
</tr>
<tr>
<td>5.1 DEPAB2 Input Data Code</td>
<td>33</td>
</tr>
<tr>
<td>5.2 Running DEPAB2 &amp; DEPAB2 Output Data Code</td>
<td>34</td>
</tr>
<tr>
<td>5.3 An Example Simulation</td>
<td>39</td>
</tr>
<tr>
<td>6. SUMMARY</td>
<td>55</td>
</tr>
<tr>
<td>7. REFERENCES</td>
<td>56</td>
</tr>
<tr>
<td>APPENDIX A:</td>
<td>57</td>
</tr>
<tr>
<td>INPUT FILE #8 FOR BOILER PARAMETERS</td>
<td></td>
</tr>
</tbody>
</table>
### List of Figures

<table>
<thead>
<tr>
<th>Figure No.</th>
<th>Description</th>
<th>Page No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Typical Fire Tube Boiler Cross-Section</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>Logics for Boiler Controllers</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>Listing of Subroutine CT</td>
<td>6</td>
</tr>
<tr>
<td>4</td>
<td>Listing of Subroutine SR</td>
<td>12</td>
</tr>
<tr>
<td>5</td>
<td>Listing of Subroutine LT</td>
<td>15</td>
</tr>
<tr>
<td>6</td>
<td>Listing of Subroutine FG</td>
<td>17</td>
</tr>
<tr>
<td>7</td>
<td>Listing of Subroutine DB</td>
<td>20</td>
</tr>
<tr>
<td>8</td>
<td>Listing of Subroutine SGHT</td>
<td>21</td>
</tr>
<tr>
<td>9</td>
<td>Listing of Subroutine SH</td>
<td>23</td>
</tr>
<tr>
<td>10</td>
<td>Subroutines for DEPAB2</td>
<td>25</td>
</tr>
<tr>
<td>11</td>
<td>Flowchart for Program DEPAB2</td>
<td>27</td>
</tr>
<tr>
<td>12</td>
<td>Listing of DEPAB2 Main Program</td>
<td>28</td>
</tr>
<tr>
<td>13</td>
<td>A Sample File 8Input Data for Boiler Parameters</td>
<td>35</td>
</tr>
<tr>
<td>14</td>
<td>Output Data from a Sample DEPAB2 Run</td>
<td>36</td>
</tr>
<tr>
<td>15</td>
<td>Control Logic for a Boiler Under Investigation</td>
<td>40</td>
</tr>
<tr>
<td>16</td>
<td>Typical Weather at Washington, D.C. During a Heating Season</td>
<td>41</td>
</tr>
<tr>
<td>17</td>
<td>Load Versus Time at a Day Whose Outdoor Air Temperature is 9.4°C (15°F)</td>
<td>42</td>
</tr>
<tr>
<td>18</td>
<td>Daily Heating Load Versus Outdoor Air Temperature</td>
<td>43</td>
</tr>
<tr>
<td>19</td>
<td>Daily Fuel Consumption Versus Outdoor Air Temperature</td>
<td>45</td>
</tr>
<tr>
<td>20</td>
<td>Daily Fuel Utilization Efficiency Versus Outdoor Air Temperature</td>
<td>46</td>
</tr>
<tr>
<td>21</td>
<td>Transient Steam Temperature at Morning Setup</td>
<td>47</td>
</tr>
<tr>
<td>22</td>
<td>Transient Stack Gas Temperature at Morning Setup</td>
<td>48</td>
</tr>
<tr>
<td>23</td>
<td>Transient Steam Temperature at Night Setback</td>
<td>49</td>
</tr>
<tr>
<td>24</td>
<td>Transient Stack Gas Temperature at Night Setback</td>
<td>50</td>
</tr>
<tr>
<td>25</td>
<td>Comparison of Heating Load and Fuel Consumption for Cases with and without Setbacks</td>
<td>54</td>
</tr>
</tbody>
</table>
1. **INTRODUCTION**

This report documents DEPAB2, a computer program for design and analysis of commercial heating boilers, which has been developed to include subroutines for (1) simulating the boiler controllers, (2) calculating combined radiative/convective heat transfer in the boiler furnace, (3) calculating combined radiative/convective heat transfer in the boiler tubes, (4) calculating off period draft air heat transfer, (5) calculating water side convective and boiling heat transfer, and (6) calculating boiler shell heat losses. Section 2 of this report describes a generalized theory of the boiler controllers and a controller subroutine CT. Elements of boiler thermodynamics and the boiler thermal flux subroutines, which includes combustion and different modes of heat transfer, are described in section 3. Also described in section 3 are thermal response equations of the boiler in lumped parametric form.

The commercial boiler transient analysis computer program is described in section 4. Detailed listings of DEPAB2 principal subroutines and the main program are included in the text of this report. Listings of auxiliary subroutines, which are used to assist with the principal subroutines' calculations, are appended to this report. A user's guide is presented in section 5. This guide includes instructions on input data preparation, output data interpretation, and running of DEPAB2 on an EXEC-1108 computer. Also included in section 5 is a worked example to demonstrate a series of DEPAB2 runs. A set of results from DEPAB2 runs are discussed in this section to illustrate how DEPAB2 may be used to facilitate engineers' design of commercial heating boilers for energy efficiency. Although the simulation program is applicable to both water tube and fire tube boilers, the development and application to date has been towards the Scotch type of fire tube boiler shown in Figure 1.
Figure 1. Typical Fire Tube Boiler (Two Pass)
2. BOILER CONTROLLER DYNAMICS AND SUBROUTINE CT

There are five types of combustion controllers which are in common use for commercial heating boilers today [1]. These controllers have three basic logics as shown in figure 2. These three basic logics are represented by: (1) the on/off controller, (2) the high/low/off controller, and (3) the air/fuel metering controller. Operational principles for these three types of controllers are as follows:

The On/Off Controller senses the boiler steam pressure (or temperature). Fuel/air supply turns on when the boiler pressure (or temperature) drops below a preset value and turns off when it rises above the same preset value.

The High/Low/Off Controller senses either the steam pressure or temperature. Air/fuel supply turns on low when the boiler pressure or temperature drops below a preset point and it turns on high when the boiler pressure or temperature drops further below another preset point. As pressure or temperature rises, the sequence reverses.

The Air/Fuel Metering Controller (or the modulating controller) has a primary feedback element sensing the boiler pressure or temperature. The output signal from the feedback element is combined with the set point signal and processed by the air/fuel automatic controller. The resultant actuating signal from the air/fuel automatic controller is used to position the final control elements for fuel/air flow in proportion to load. There is usually a minimum firing rate for a boiler burner; so a boiler with an air/fuel metering controller operates in an on/off mode when the heating load for the boiler is smaller than the boiler steady-state output at its minimum firing rate.
FIGURE 2
LOGICS FOR GENERALIZED COMBUSTION CONTROLLERS
Curves of steady-state air and fuel flow rates versus the boiler pressure or temperature are shown in figure 2 for boilers with the three different types of controllers discussed above. In a transient state, instantaneous air/fuel flow rate ($w_a$ and $w_f$) may lag behind the steady-state values (i.e., the RF and RA values read from figure 2). In terms of the steady-state values and the time lag constant, the on and off cycle air/fuel flow rates can be calculated from the equation:

$$\frac{dw}{dt} = \frac{1}{\tau}(R-w) \quad (1)$$

where $w$ is the instantaneous air or fuel flow rate; $\tau$ the on or off period air/fuel flow time constant, and $R$ the steady-state air or fuel flow rate (i.e., the RA or RF value read from figure 2). Input to the controller is, therefore the control variable (i.e., pressure or temperature); and its outputs are the air and fuel flow rates. Time constants for air/fuel flows and relations of steady state air/fuel flow rates to the boiler control variable are the controller parameters. According to the controller dynamics described above, subroutine CT has been written to calculate the controller dynamic responses. Figure 2 shows a detailed listing of subroutine CT.
SUBROUTINE CT(ONF, WFUEL, WAIR, WGAS, TSEN, JCTBL, ICTYPE, TASEN, TAAIR, AIROF, DT)

C     CALCULATE CONTROLLER STATUS
C
COMMON/CONTRL/TBOIL(8), FRGBL(8), AIRBL(8)
COMMON/ WRITE/IWRITE
TSEN=TSEN*(DT/TASEN) *(TBL-TSEN)
GOTO(100, 290, 300), ICTYPE
100 IF(ONF. CT. 0.5. AND. TSEN.GE.TBOIL(7)) GOTO110
110 ONF=0.
120 ONF=1.
WFUEL=FRGBL(6)
WAIR=AIRBL(6)
GOTO600
200 IF(ONF. LT. 0.5) GOTO210
210 IF(TSEN. CT. TBOIL(7)) GOTO500
ONF=1.
WFUEL=FRGBL(7)
WAIR=AIRBL(7)
GOTO600
220 IF(TSEN. CT. TBOIL(6) .AND. TSEN.LT. TBOIL(7)) GOTO500
224 ONF=0.
GOTO500
228 ONF=2.
WFUEL=FRGBL(6)
WAIR=AIRBL(6)
GOTO600
230 IF(TSEN. LT. TBOIL(7)) GOTO500
ONF=1.
WFUEL=FRGBL(7)
WAIR=AIRBL(7)
GOTO600
300 NP=8
310 IF(TSEN. GE. TBOIL(8)) GOTO315
315 ONF=1.
WFUEL=TAB1(NP, TBOIL, FRGBL, TSEN)
WAIR=TAB1(NP, TBOIL, AIRBL, TSEN)
GOTO300
310 IF(TSEN. GE. TBOIL(7)) GOTO310
315 ONF=1.
WFUEL=TAB1(NP, TBOIL, FRGBL, TSEN)
WAIR=TAB1(NP, TBOIL, AIRBL, TSEN)
GOTO300
500 IF(ONF. CT. 0.5) GOTO600
WFUEL=0.
WAIR=WAIR*(DT/TAAIR) *(AIROF- WAIR)
600 WGAS=WAIR*WFUEL
RETURN
END

FIGURE 3 LISTING OF SUBROUTINE CT
3. **BOILER THERMAL DYNAMICS AND SUBROUTINES**

The main thermal elements of a boiler are:

- Combustion gas and air
- Boiler Furnace Wall and Tube Walls
- Water and steam
- Boiler Shell

With the above elements divided into elementary sections, energy balance equations can be written for each finite element:

**For Combustion Gas or Draft Air:**

\[
\frac{dT_g}{dt} = \left(\frac{1}{C_p} \right)_g \left[ (C_p \rho g) (T_1 - T_2) - Q_{gw} \right]
\]

where \( W \) is defined as the mass flow rate (on page 8).

**For Boiler Furnace and Tube Walls:**

\[
\frac{dT_w}{dt} = \frac{1}{(C_p m)_w} \left( Q_{gw} - Q_{wf} \right)
\]

**For Water or Steam**

\[
\frac{dT_f}{dt} = \frac{1}{(C_p m)_f} \left( [w_f (h_1 - h_2)]_f + Q_{wf} \right)
\]
For Boiler Shell

\[
\frac{dT_s}{dt} = \frac{1}{(C_m)_s} (Q_{ws} - Q_{sa}) \tag{5}
\]

In the above equations, \( w \) is the mass flow rate, \( t \) the temperature, \( h \) the specific enthalpy, \( C_p \) the specific heat at constant pressure, \( t \) the time, \( Q \) the heat transfer rate, and \( m \) the mass. Subscripts 1 and 2 are for the section inlet and output ports, respectively; and subscripts \( g, w, f, s, \) and \( a \) are for gas (or air), solid wall, fluid, boiler shell and ambient air, respectively. A compound suffix indicates an interface condition. For example, \( Q_{gw} \) indicates heat transfer rate from the combustion gas (or draft air) to the boiler furnace (or tube) wall.

Simplication can be made to the above differential equations to reduce the number of state variables.* For the gas (or air), its heat capacitance can always be neglected. Equation 2 can then be reduced to an algebraic equation

\[
Q_{gw} = (C_w) (T_1 - T_2) \tag{6}
\]

For the boiler, the water capacitance is commonly larger than the furnace (or tubes) wall capacitance. To increase calculation efficiency, the wall capacitance can be added to the water capacitance. Combination of equations 3 and 4 yields

*A state variable is a variable whose first derivative with respect to time is equal to a linear combination of other variables.
a state variable equation for the water temperature:

$$\frac{dT_f}{dt} = \frac{1}{[(C_{pm})_w + (C_{pm})_f]} \{[w(h_1 - h_2)] + Q_{gw}\} \tag{7}$$

The wall temperature can then be calculated from the equation:

$$T_w = T_f + \frac{1}{(A\alpha)_wf}(Q_{gf}) \tag{8}$$

where $A$ and $\alpha$ are the heat transfer area and coefficient, respectively.

With the above simplifications, temperatures for elements of combustion gas, draft air, furnace wall, and boiler tubes are no longer state variables. Besides flow rates for the combustion gas and draft air (see equation 1), temperatures of the boiler water and shell elements are the other state variables (see equations 5 and 7). Methods for solving equations 1, 5 & 7 are readily available; and among the best known are the standard Euler and Runge-Kutta procedures [2]. However, in a boiler environment, the heat transfer rate $Q$ needs careful formulation for individual elements of the boiler in order to insure the model's validity. Accordingly mathematical models and computer subroutines for calculating heat fluxes that occur within commercial boilers have been developed in the following five sections for (1) the boiler furnace at on period, (2) the boiler tubes at on period, (3) the boiler furnace and tubes at off period, (4) the water/tube interface, and (5) the boiler shell.
3.1 **Math Model and Subroutine SR for Gas/Furnace Heat Flux at On period**

Starting from the products of combustion at the adiabatic flame temperature, the heat flow \( Q_{gw} \) from the combustion gas to the furnace wall is by radiation and convection. It was determined from stirred reactor theory [3] that the \( Q_{gw} \) value can be calculated from the equation:

\[
Q_{gw} = \left[ A_{GS} \left( \frac{1 - K^3}{1 - K^4} \right) + A_s \frac{2\alpha_c}{\sigma (T_{AG} + T_S)^3} \right] \sigma (T_{AG}^4 - T_S^4) \tag{9}
\]

where \( A_{GS} = \frac{A_S + A_R}{\varepsilon_G + \frac{1}{C_S \varepsilon_S} - 1} \) for total gas/sink radiative exchange area

- \( A_R \) = refractory surface area
- \( A_S \) = sink surface area
- \( C_S \) = ratio of \( A_S \) to \( A_S + A_R \)
- \( \sigma \) = Stefan-Boltzmann constant
- \( \alpha_c \) = convective heat transfer coefficient
- \( \varepsilon_G \) = gas emissivity
- \( \varepsilon_S \) = sink surface emissivity
- \( T_{AG} = 0.5 (T_{AF} + T_{EG}) \), average furnace gas temperature
  where \( T_{AF} \): adiabatic flame temperature
  \( T_{EG} \): temperature of exit gas from furnace
K = T_s / T_{AC}', ratio of the sink surface to the furnace gas temperature

The convective heat transfer coefficient, $a_c$, in equation 9, can be calculated by McAdams' correlation equation [4]:

$$a_c = 0.023 \frac{k}{D} (Re)^{0.8} (Pr)^{0.4}$$  \hspace{1cm} (10)

A computer subroutine SR has been written (using the above equations) to calculate the gas/furnace wall interface heat flux at on period. Inputs to SR are the air/fuel flow rates and temperatures at the furnace inlet, and the furnace wall temperature. Outputs from SR are the gas/wall interface heat flux, and temperature of combustion gas at the furnace outlet. A detailed listing of subroutine SR is shown in figure 4.

3.2 Math Model and Subroutine LT for Gas/Tube Heat Flux at On Period

Banks or passes of tubes are present in commercial boilers. These tubes can be divided into elementary sections in the gas flow direction. For each elementary section, there is a distinctive
SUBROUTINE SR(PTOTAL, PC02, PH20, PS02, P02, PN2, RATF, RWTF, RPTF,\
%HFUEL, CPFUEL, TFUEL, BTUHK, EXAIR, TAIR,\
%FVOL, FSA, FRA, FDIAM, FSEM, TS, Q, TAF, TCE)

*** SIMULATE STIRRED REACTORS

COMMON/WRITEX/WRITE
HHV=HFUEL+CPFUEL*(TFUEL-TAIR)
W=1000.*BTUHK/HHV
ERR=0.001
CP1=0.24
CP=0
PTT=14.7*PTOTAL
WRITE(6,904)PTOTAL, PC02, PH20, PS02, P02, PN2, RATF, RPTF,\
%HFUEL, CPFUEL, TFUEL, BTUHK, EXAIR, TAIR,\
%FVOL, FSA, FRA, FDIAM, FSEM
710 CONTINUE
904 FORMAT(3(6(1PE11.3))/,1PE11.3)

TRS=TS+459.67
TA=TAIR+459.67
TAF=TFUEL+459.
W=W*RPTF
WH20=18.*PH20/(44.*PC02+32.*P02+64.*PS02+28.*PN2)
IF(IWRITE.LE.1)GOTO712
WRITE(6,906)WH20
712 CONTINUE
906 FORMAT(2X,'WH20=',1PE11.3)

SIGMA=0.1713E-08
AC=0.78539316*FDIAM*FDIAM
ALF=9
BLF=0
CLF=0
ATOTAL=FSA+FRA
CS=FSA/ATOTAL
AL=3.5*FVOL/ATOTAL

CALCULATE ADIABATIC FLAME TEMPERATURE

TAF=TAFF(HHV, RWTF, RPTF, PC02, PH20, P02, PS02,\
PN2, CP1, TRA, ERR, CP)
IF(IWRITE.LE.1)GOTO700
WRITE(6,900)TAF
700 CONTINUE

CALCULATE RADIATIVE HEAT TRANSFER

IF(IWRITE.LE.1)GOTO766
WRITE(6,902)
766 CONTINUE
TC2=TAF-500
ITR=0
300 ITR=ITR+1
TAG=0.5*(TAF+TC2)
CP0E=CPF(TRA, TC2, PC02, PH20, P02, PS02, PN2)
CPAE=CPF(TC2, TAF, PC02, PH20, P02, PS02, PN2)
CP0A=CPF(TRA, TAF, PC02, PH20, P02, PS02, PN2)
I=2
TT=TAG-459.67
CALL PRDPR(TT, PC02, PH20, P02, PN2, PS02, AMU, AKK)

FIGURE 4 LISTING OF SUBROUTINE SR
FIGURE 4 (CONTINUED)
characteristic that their length in the direction of gas flow is much greater than the radiative width or height so that net radiative flux in the gas flow direction may be ignored relative to flux normal to it. Long-tube analysis [3] can be used to calculate the radiative heat flux at the gas/tube interface. Equations for long-tube analysis, including both the radiative and convective heat fluxes, have been derived. A calculation sequence is as follows:

\[ a_c = a(Re)^b(Pr)^c \left( \frac{k}{D} \right)^c, \text{ for convective heat transfer coefficient} \]  
\[ \alpha_r = \frac{4\sigma T^3}{1 + \frac{1}{\varepsilon_G} - 1 - \frac{\varepsilon_S}{1}}, \text{ for radiative heat transfer coefficient} \]  
\[ \alpha = \alpha_c + \alpha_r, \text{ overall heat transfer coefficient} \]  
\[ Q_{gw} = (C_p \rho g) (T_i - T_w)(1 - \exp\left(-\frac{Aa}{C_p \rho g} \right)), \text{ for gas/tube interface heat flux} \]  

Using the above calculation sequence, a computer subroutine LT has been written to calculate the gas/tube interface heat flux. A detailed listing of LT is shown in figure 5.
SUBROUTINE LT(TGI, TS, PTOTAL, PC02, PE20, PS02, PN2, P02, WGAS, 
GAS, GSVL, GSAC, GSCD, GSA, GSB, GSC, GSE, Q, TGE)

*** LONG TUBE REACTORS

INPUT DATA:
TGI  GAS INLET TEMPERATURE  F
TS   WALL SURFACE TEMPERATURE  F
PTOTAL  TOTAL PRESSURE  ATM
PC02  MOLE FRACTION FOR CO2
PE20  MOLE FRACTION FOR H2O
PS02  MOLE FRACTION FOR O2
PN2   MOLE FRACTION FOR N2
P02   MOLE FRACTION FOR O2
WGAS  GAS FLOW RATE  LB/HR
GAS   SURFACE AREA  SQFT
GSVL  VOLUME  CUFT
GSAC  FLOW CROSS SECTIONAL AREA  SQFT
GSCD  HEAT TRANSFER CHARACTERISTIC DIMENSION  FT
GSA   COEFFICIENT IN NU EXPRESSION
GSB   COEFFICIENT IN NU EXPRESSION
GSC   COEFFICIENT IN NU EXPRESSION
GSE   TUBE SURFACE EMISSIVITY

OUTPUT DATA:
Q   HEAT TRANSFER RATE  BTU/HR
TGE GAS EXIT TEMPERATURE  F

*** CALCULATION BEGINS:
TAV=0.5*(TGI+TGE)
TGI=TGI+459.67
TGE=6.33*GSCD/GSAS
PPC02=PC02*PTOTAL
PPH20=PE20*PTOTAL
EMGS=GEF(PPC02,PPH20, XL, TGS)
SIGMA=0.1713*0.8
HALL=1./GSE*1./EMGS-1.
HALL=4.*SIGMA*TAV**3/HALL
CPW=CPCAS*WAS
ANTU=GAS*HALL/CPW
Q2=(TGI-TS)*(1.-EXP(-ANTU))
TGE=TGI-Q2
Q=CPW*Q2
RETURN
END

FIGURE 5 LISTING OF SUBROUTINE LT
3.3 Math Model and Subroutine FG for OFF Period
Gas/Solid Interface Heat Transfer

During the off period, draft air flows through the boiler furnace and tubes. Air can be considered to be radiatively transparent; so air/boiler interface heat transfer at the off cycle is by pure convection. The convective heat transfer coefficient can be calculated from the equation [3]:

\[ h = a (Re)^b (Pr)^c \left( \frac{k}{D} \right) \]  (15)

and the interface heat flux can then be calculated from the equation

\[ Q_w = (C_w) g (T_1 - T_w)[1 - \exp\left(\frac{-Aa}{C_w g}\right)] \]  (16)

A computer subroutine FG has been written (using the equations 15 and 16) to calculate heat flux at the interface of the draft air and the boiler furnace or tube wall. A detailed listing of subroutine FG is shown in figure 6.

3.4 Subroutines DB and SGHT for Water Side Heat Transfer

With heat fluxes calculated by the equations discussed
SUBROUTINE FG(QCT, TGS, 
*TTB, WAIR, PAIR, TAIR, AC, AS, D, ALF, BLF, CLF)
C
C *** OFF-CYCLE GAS/FURNACE HEAT TRANSFER
C
I=1
C RH=0.5
C PNW=PAIR
C TR=460.+TAIR
C CC=(TR/660.)**0.75
C CP=0.24
C AK=0.018*CC
C AM=0.052*CC
C RH=0.
CALL AIRPR(I, TAIR, PAIR, RE, SH, CP, R, AM, AK) 
PR=PRNB(AM, CP, AK)
RE=RENB(WAIR, AM, AC, D)
ALPHA=SGHT(RE, PR, AK, D, ALF, BLF, CLF)
CPV=CP*WAIR
ANTU=ALPHA*AS/CPW
DELT=(TAIR-TTB)*(1.-EXP(-ANTU))
TGS=TAIR-DELT
QCT=CP*DELT
RETURN
END

FIGURE 6 LISTING OF SUBROUTINE FG

17
immediately above, the furnace and tube wall temperature can now be calculated from equation 8. The water/solid interface heat transfer coefficient in equation 8 can be calculated by either of the following two equations, depending upon whether the water temperature is at or below the boiling point temperature corresponding to the boiler pressure:

\[
\alpha = 76.92 (Re)_B^{0.067} Pr^{0.7} \left( \frac{k}{D_B} \right) \\
\alpha = 0.023(Re)^{0.8}(Pr)^{0.4} \left( \frac{k}{D} \right)
\]

(17) 

(18)

These two equations will be used in different ranges of water temperature and give us a better result.

Equation 17 above is a correlation equation for nucleate boiling obtained by Rohsenow [5], and equation 18 is the familiar equation for convective heat transfer due to McAdams [4]. In evaluating equation 17, the boiling bubble diameter is used to calculate the \((Re)_B\) and \((k/D_B)\) instead of the usual hydraulic diameter which is used to calculate \((Re)\) and \((k/D)\) for equation 18. The following equation can be used to calculate the bubble diameter \(D_B\):

\[
D_B = \frac{\gamma}{g \left( \frac{\rho_l}{\rho_v} - \rho_v \right)}
\]

(19)

where
\[
\gamma = \text{water surface tension coefficient} \\
g = \text{gravitational acceleration} \\
\rho_l = \text{water density}
\]
\[ \rho_v = \text{steam density} \]

Subroutines DB and SGHT have been written to calculate the water side convective and boiling heat transfer coefficients. Detailed listing of these subroutines are shown in figures 7 and 8.

3.5 Subroutine SH for Boiler Shell Heat Loss

The heat loss at the boiler shell \( Q_{sa} \) can be calculated from the equation:

\[ Q_{sa} = UA(T_f - T_a) \]

where

- \( U \) = overall heat transfer coefficient
- \( A \) = shell area
- \( T_f \) = water temperature
- \( T_a \) = ambient air temperature

The value of \( U \) in the above equation is calculated using the heat transfer coefficient values for the series of thermal layers including the water/shell interface, shell wall, and shell/air interface:

\[ U = \frac{1}{(1/\alpha_{fs} + 1/\alpha_s + 1/\alpha_{sa})} \]
FUNCTION DB(ROL, ROV, SIGMA)

*** CALCULATE NUCLEATION BUBBLE DIAMETER

INPUT DATA:

ROL LIQUID DENSITY LB/CUFT
ROV VAPOR DENSITY LB/CUFT
SIGMA SURFACE TENSION LB/FT

OUTPUT DATA:

DB DIAMETER OF BOILING NUCLEATION BUBBLES FT

DB = SQRT(SIGMA / ((ROL-ROV) * 32.174))
RETURN
END

FIGURE 7 LISTING OF SUBROUTINE DB
FUNCTION SGHT(RE, PR, AK, D, ALF, BLF, CLF)

C *** CALCULATE SINGLE-PHASE HET TRANSFER COEFFICIENT
C

COMMON WRITE/1WRITE
WRITE(6,706) RE, PR, AK, D, ALF, BLF, CLF

704 CONTINUE
706 FORMAT(/2X,5HSQHT,:/2X,2HRE,9X,2HPR,9X,2HAK,9X,1HE/
%4(1PE11.3)/2X,3HBLF,6X,3HBLF,8X,3HCLF/3(1PE11.3))
TALF=ALF
TBLF=BLF
TCLF=CLF
IF (TALF.GE.1.E-10) GOTO 10
IF (RE.GE.2000.) GOTO 20
TALF=3.66
TBLF=0.
TCLF=0.
GOTO 10
20 TALF=0.923
TBLF=0.8
TCLF=0.4

10 SGHT=TALF*AK*RE**1.00*TBLF*PR**TCLF/D
IF (1WRITE.LE.1) GOTO 700
WRITE(6,702) SGHT

700 RETURN
702 FORMAT(/2X,5HSQHT*,1PE11.3)
END

FIGURE 8 LISTING OF SUBROUTINE SGHT
In this equation, \( \alpha_{fs} \) is calculated by McAdams' equation:

\[
\alpha_{fs} = 0.023(\text{Re})^{0.8}(\text{Pr})^{0.4} \left( \frac{k}{D} \right) \tag{22}
\]

\( \alpha_{s} \) is calculated by the wall conductance equation:

\[
\alpha_{s} = \frac{k}{x} \tag{23}
\]

and \( \alpha_{sa} \) is calculated by the free convective equation

\[
\alpha_{sa} = 0.29(\Delta T/L)^{0.25}, \text{ for } L^3 \Delta T < 10^3 \tag{24}
\]

or

\[
\alpha_{sa} = 0.21(\Delta T)^{0.333}, \text{ for } L^3 \Delta T > 10^3 \tag{25}
\]

These equations have been used to write a subroutine \textit{SH} for calculating the heat loss at the boiler shell. A detailed listing of subroutine \textit{SH} is shown in figure 9.

3.6 Auxiliary Subroutines

The six subroutines for calculating the boiler heat flux
SUBROUTINE SH(Q, TS, TW, TA, UW, AREA, US, AL)

C *** CALCULATE SHELL HEAT TRANSFER

C

R1 = 1. / AIRFHT(TS, TA, AL)
R2 = 1. / US
R3 = 1. / UW
AU = AREA / (R1 + R2 + R3)
Q = AU * (TW - TA)
TS = TW - Q * (1. / (AREA * (US + UW)))
RETURN
END

FIGURE 9  LISTING OF SUBROUTINE SH
have been described in the previous 5 subsections. These six heat flux subroutines together with the controller subroutine discussed in the previous section form seven principal subroutines for the commercial boiler transient analysis computer program DEPAB2. Figure 10 summarizes names and purposes of these seven principal subroutines. Also listed in figure 10 are auxiliary subroutines used to assist with the principal subroutines calculations. It can be seen in figure 10 that the auxiliary subroutines can be categorized into three groups of: (1) fluid properties, (2) fuel/air combustion, and (3) heat transfer parameters. Detailed listings of these auxiliary subroutines are appended to this report.
PRINCIPAL SUBROUTINES FOR DEPAB2

BOILER CONTROLLER CT
ON PERIOD FURNACE HEAT TRANSFER SR
ON PERIOD BOILER TUBES HEAT TRANSFER LT
OFF PERIOD DRAFT AIR HEAT TRANSFER FG
FEEDWATER HEATING SGHT
NUCLEATE BOILING HEAT TRANSFER DB
BOILER SHELL HEAT LOSS SH

AUXILIARY SUBROUTINES FOR DEPAB2

FLUID PROPERTIES:

AIR PROPERTIES AIRPR
WATER PROPERTIES H2OLQ
STEAM PROPERTIES H2OVP
COMBUSTION PRODUCTS \( u \) & \( k \) PRDPR
COMBUSTION PRODUCTS \( C_p \) CPF

FUEL/AIR COMBUSTION:

PRODUCTS OF COMBUSTION PP
ADIABATIC FLAME TEMPERATURE TAFF
FUEL AIR FLOW RATES GF
AMOUNT OF EXCESS AIR BG

HEAT TRANSFER PARAMETERS:

REYNOLDS NUMBER RENB
PRANDTL NUMBER PRNB
FREE CONVECTION HEAT TRANSFER FOR AIR AIRFHT
GAS RADIATIVE EMISSIVITY GEF
GAS/SINK RADIATIVE EXCHANGE AREA GS
OVERALL HEAT TRANSFER COEFFICIENT OVHT
LOOKUP OF TABULATED DATA TAB1

FIGURE 10 SUBROUTINES FOR DEAPB2
One controller subroutine and six heat flux subroutines described in the previous two sections are merged together to form DEPAB2. The controller subroutines can be used to calculate the air/fuel rates and heat flux subroutines to calculate heat fluxes at different parts of the boiler (which include the boiler furnace, tubes in sections and shell). The transient response of the boiler can then be calculated from equations 6 to 8 (i.e.: equation 6 for outlet gas temperatures at furnace and tube sections outlets, equation 7 for boiler water temperatures, and equation 8 for boiler furnace, tube sections, and shell temperatures).

DEPAB2 start by reading in the boiler parameters, load schedules, and initial values. It then calculates interface heat fluxes by calling up the principal subroutines described in the preceding section. Transient time histories of the boiler temperatures and performance are then calculated. Finally, overall performance of the boiler over a chosen duration of simulation is calculated and printed out.

Figure 11 shows a flowchart for DEPAB2; and a detailed listing of DEPAB2 is shown in figure 12.
FIGURE 11  FLOWCHART FOR DEPAB2

-27-
**PROGRAM NAME**: DEPAB2

**PURPOSE**: SIMULATE LARGE-SCALE BOILERS

**INPUT FILE**

```plaintext
COMMON/WRITE/INITIZ
COMMON/FILE/TMP(76), TIA(60), TDA(50), XMD(60)
COMMON/CONTROL/TSOL(.2), FCGEL(.3), AIREL(.8)
DIMENSION TSH(51), TTH(51), TVT(81), GQT(81)
DIMENSION TCM(90), FULR(80), TC(90), TDI(50),
        XTRA(50), TBB(50), TBE(50), TBE(50)
DOS=.181
TSH(2)=8.0
TTH(2)=.8
GQT(1)=.8
IF(1.EQ.3) GOTO 31
TAS(1)=.8
TVL(2)=.8
TAC(1)=.8
TD(1)=.8
TBA(1)=.8
TBB(1)=.8
TBC(1)=.8
TBE(1)=.8
CONTINUE
```

**INPUT DATA**

```plaintext
WRITE(6,996)
READ(3,.#) WRITE
```

**INPUT FUEL DATA**

```plaintext
FUEL=1.
PAIR=FUEL=6.7
READ(3,.#) CARB, HYD, OXYG, XTR, SULF
WRITE(6,996) CARB, HYD, OXYG, XTR, SULF
READ(3,.#) HFUEL, CFUEL, TFUEL, STOKE
WRITE(6,996) HFUEL, CFUEL, TFUEL, STOKE
```

**INPUT CONTROL SUBSYSTEM DATA**

```plaintext
DOS=1.8
TSH(1)=1.8
TTH(1)=1.8
AIREL(1)=1.8
READ(8,.#) ICTYPE
WRITE(6,416) ICTYPE
READ(8,.#) TASEN, TAIR, FNGEL, EXAFL, AIROF
WRITE(6,416) TASEN, TAIR, FNGEL, EXAFL, AIROF
CALL PP(FTOTAL, CARB, HYD, OXYG, XTR, SULF, SULF, EXAFL,
        MPO2, FS02, PS02, FS2, FFAT, RPTF, RVTF)
WRITE(6,996) RVTY=# (1650./HFUEL)
AIROF=AIROF=AIROF
TAIR=TAIR=TAIR
WRITE(6,405) TASEN, TAIR, FNGEL, AIROF
GOTO(21,22,23,3), ICTYPE
```

**INPUT WATER DATA**

```plaintext
WRITE(6,917)
DO31=11., 12
READ(8,.#) TSOL(1), FNGEL(1), AIREL(1)
DO31=1, 2
WRITE(6,883) TSOL(1), FNGEL(1), AIREL(1)
FNGEL(1)*FNGEL(1) AIREL(1)
AIREL(1)*AIREL(1)
WRITE(6,883) TSOL(1), FNGEL(1), AIREL(1)
```

**INPUT FURNACE DATA**

```plaintext
READ(8,.#) FUTL, PCA, PCA, FRA, FDIAM, PRESS
WRITE(6,994) FUTL, PCA, PCA, FRA, FDIAM, PRESS
READ(8,.#) PCA, PCA, PCA, FC
WRITE(6,923) PCA, PCA, PCA
```

**FIGURE 12** LISTING OF DEPAB2 MAIN PROGRAM
**INPUT TUBE DATA**

```plaintext
READ(8,*)NJ1,NJ2
WRITE(6,925)NJ1,NJ2
K=1
L=NTN
DO40J=1,2
IF(J.EQ.1)GOTO44
K=K+1
L=L+NTN
```

**INPUT WATER DATA**

```plaintext
READ(8,*)STFV,WTAG,WTCD,WTA,WTB,WTC
WRITE(6,911)STFV,WTAG,WTCD,WTA,WTB,WTC
STFV=0.9*STFV
WTAG=WTA
```

**INPUT SHELL AND WEIGHT DATA**

```plaintext
READ(8,*)SHARE,SHUPT,SHHGT,SHCAP,PNCAP,TBCAP,WTCAP
LOADSHEULING*
```

**INITIAL VALUES**

```plaintext
WRITE(6,935)
READ(5,*)ICYCLE
WRITE(6,9000)
READ(5,*)TANTE,D1,IPRNT,ICALC
TANTE=TANTE
WRITE(6,9042)
READ(5,*)NUM,TSRN,TBL
DSGNS=1.
```

**CALCULATION BEGINS**

```plaintext
ICYCLE=1
TANTE=0.
QUDCTC=0.
QIFNOW=0.
STAMP=0.
```

FIGURE 12 (CONTINUED)
FIGURE 12 (CONTINUED)
FIGURE 12 (CONTINUED)
5. USER'S GUIDE

To assist users of DEPAB2, details of the (1) DEPAB2 input code, and (2) DEPAB2 running procedure and output code are given in this section. Also included is a worked example to demonstrate DEPAB2 runs.

5.1 DEPAB2 Input Data Code

As described in the previous sections, there are three types of input data for DEPAB2. They are:

(1) boiler parameters,
(2) boiler load status, and
(3) boiler initial conditions.

File 8 is used to enter the type 1 data; and file 5 (terminal at interactive mode) is used to enter the type 2 and 3 data.

To assist the user with the preparation of files 8 and 5, the input data code for file 8 is fully interpreted in appendix A and the data code for File 5 in appendix B.

While a majority of the terminology used in files 8 and 5 are self explanatory, input (ICTYPE=1, 2 or 3) refers to the generalized controller types shown in figure 2. A familiarization of the input data code in appendices A and B can facilitate the reader's use of DEPAB2.
Running DEPAB2 &
DEPAB2 Output Data Code

Each run of DEPAB2 includes three major steps. They are:

(1) Prepare file 8 for the boiler and its controller parameters,

(2) Enter the boiler operational schedules and its initial conditions at the terminal or through file 5, and

(3) Execute DEPAB2 using the execution command.

Figure 13 shows a copy of file 8 which represents a commercially available 400 boiler horsepower fire-tube boiler. Figure 14 shows a DEPAB2 run using file 8 data. The terminal input (file 5) of this run can be observed on the printout shown in figure 14, following echoes of the input data from file 8.

After input data for the boiler parameters, operational schedules, and initial conditions have been read in, DEPAB2 executes the calculations and outputs results in accordance with the sequence shown in the DEPAB2 flowchart (see figure 2). Interpretation of the DEPAB2 output data code is given in appendix C.
100 0.207, 0.790, 0.0023, 0.0016, 0.00
110 23400., 0.52, 65., 16750.
120 3
130 2., 2., 716., 0.25, 0.3
140 220., 1., 1.
150 224., 0.9, 0.9
160 228., 0.8, 0.8
170 232., 0.7, 0.7
180 236., 0.6, 0.6
190 240., 0.5, 0.5
200 244., 0.4, 0.4
210 250., 0.4, 0.4
220 2., 200., 212.
230 264., 145., 10.6, 21., 3.67, 0.8
240 0.023, 0.8, 0.4
250 5, 10
260 50., 19., 0.5, 0.21, 0.023, 0.8, 0.4, 0.8
270 50., 19., 0.5, 0.21, 0.023, 0.8, 0.4, 0.8
280 250., 18., 2.67, 0.33, 0.6, 0.33
290 380., 54., 8., 1710., 337., 1500., 7500.
END OF FILE

FIGURE 13 A SAMPLE FILE 8 INPUT DATA FOR BOILER PARAMETERS
<table>
<thead>
<tr>
<th>IWRITE=</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>CARB</td>
<td>HYDR</td>
</tr>
<tr>
<td>2.070-001</td>
<td>7.900-001</td>
</tr>
<tr>
<td>HFUEL</td>
<td>CPFUEL</td>
</tr>
<tr>
<td>2.340+004</td>
<td>5.200-001</td>
</tr>
<tr>
<td>ICTYPE=</td>
<td>3</td>
</tr>
<tr>
<td>TASEN</td>
<td>TAAIR</td>
</tr>
<tr>
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<td>2.000+000</td>
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<tr>
<td>TBOIL</td>
<td>FRGBL</td>
</tr>
<tr>
<td>2.200+002</td>
<td>1.000+000</td>
</tr>
<tr>
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</tr>
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<td>4.000-001</td>
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<td>2.864+002</td>
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<td>TIN</td>
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<td>2.000+002</td>
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</tr>
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<td>TBE</td>
</tr>
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<td>1.900+001</td>
</tr>
<tr>
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<td>8.000-001</td>
</tr>
<tr>
<td>5.000+001</td>
<td>1.900+001</td>
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<td>8.000-001</td>
</tr>
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<td>WTAC</td>
</tr>
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<td>1.800+001</td>
</tr>
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<td>SHUTF</td>
</tr>
<tr>
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<td>5.400+001</td>
</tr>
<tr>
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<td>TBCAP</td>
</tr>
<tr>
<td>3.370+002</td>
<td>1.500+003</td>
</tr>
</tbody>
</table>

**Figure 14**  
**OUTPUT DATA FROM A SAMPLE DEPAB2 RUN**
NTIME=?

>3
TMIN, TIA, TOA, HDMD=?

>60, 70, 45, 4170000.

-6.000+001 7.000+001 4.500+001 4.170+006

TMIN, TIA, TOA, HDMD=?

>0, 70, 45, 4170000.

0.000 7.000+001 4.500+001 4.170+006

TMIN, TIA, TOA, HDMD=?

>60, 70, 45, 4170000.

6.000+001 7.000+001 4.500+001 4.170+006

ICYCLE=?

>0
TIME, DT, IPRNT, ICALC=?

>-30, 0.5, 20, 60
ONF, TSEN, TBL=?

>1, 240, 240,
TSH, TRW=?

>220, 180.

**FIGURE 14 (CONTINUED)**
### OUTPUT DATA FROM DEPAB2 RUN:

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<thead>
<tr>
<th>Time:</th>
<th>QSUPLD</th>
<th>QLOAD</th>
<th>QFWAT</th>
<th>QSHELL</th>
<th>QEXHT</th>
<th>QLTNT</th>
</tr>
</thead>
<tbody>
<tr>
<td>-2.000+001</td>
<td>8.187+006</td>
<td>4.170+006</td>
<td>2.706+005</td>
<td>5.555+004</td>
<td>4.646+005</td>
<td>7.837+005</td>
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<tr>
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<td>2.270+003</td>
<td>4.303+002</td>
<td>7.736+002</td>
<td>3.012+002</td>
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<td>4.397+006</td>
<td>5.370-001</td>
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<td>0.000</td>
<td>0.000</td>
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<tr>
<td></td>
<td>8.060+006</td>
<td>4.170+006</td>
<td>2.792+005</td>
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<td>2.877+005</td>
<td>5.704+004</td>
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<td>2.238+003</td>
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<td>2.996+002</td>
<td>2.452+002</td>
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### TIME:

<table>
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<th>QFWAT</th>
<th>QSHELL</th>
<th>QEXHT</th>
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<td>3.017+005</td>
<td>5.828+004</td>
<td>3.297+005</td>
<td>6.639+005</td>
</tr>
<tr>
<td>2.162+003</td>
<td>4.072+002</td>
<td>7.432+002</td>
<td>2.914+002</td>
<td>2.475+002</td>
<td>2.434+002</td>
<td></td>
</tr>
<tr>
<td>6.937+006</td>
<td>4.435+006</td>
<td>6.393-001</td>
<td>1.817+006</td>
<td>1.476+006</td>
<td>8.126-001</td>
<td></td>
</tr>
<tr>
<td>3.000+001</td>
<td>6.700+006</td>
<td>4.170+006</td>
<td>3.068+005</td>
<td>5.875+004</td>
<td>2.967+005</td>
<td>6.413+005</td>
</tr>
<tr>
<td>2.138+003</td>
<td>3.966+002</td>
<td>7.375+002</td>
<td>2.886+002</td>
<td>2.485+002</td>
<td>2.445+002</td>
<td></td>
</tr>
</tbody>
</table>

ICONTINUE=?

>0

**FIGURE 14** (CONTINUED)
5.3 An Example Simulation

A series of computer runs for a commercially available 400-HP fire tube boiler are described below. During these runs, the boiler is assumed to have a type-3 controller. It proportions the air/fuel input as long as the value for the controlled variable (i.e., steam temperature in this example) is below a preset value. After the steam temperature rises above this preset value, the boiler is supplied with a predetermined low fuel/air input. If the steam temperature rises further above a second preset value, the boiler fuel supply will be turned off. Figure 15 shows a control logic for this control scheme.

A DEPAB2 simulation of this boiler under a series of different operational conditions (i.e., weather, heating load, night setback, etc.) was made. A sample set of runs using Washington D.C. weather data, shown in figure 16, is presented here. The boiler heating load is assumed to be proportional to the ΔT of 70°F minus the outdoor air temperature. The boiler is 20% oversized at the design outdoor temperature of 10°F for Washington D.C. Figure 17 shows the heating load for this boiler under the conditions of with and without night setbacks*, respectively, with the outdoor temperature being 15°F. The daily heating load for this boiler at different outdoor temperatures is shown in figure 18.

*With night setbacks, heating load at night is assumed to be 40% of that at the day time.
Figure 15  CONTROL LOGIC FOR A BOILER UNDER INVESTIGATION
FIGURE 16  TYPICAL WEATHER AT WASHINGTON D.C. DURING THE HEATING SEASON

OUTDOOR AIR TEMPERATURE, °F

DAYS PER HEATING SEASON
FIGURE 17 LOAD VERSUS TIME FOR A DAY WHOSE OUTDOOR AIR TEMPERATURE IS 15°F
FIGURE 18  DAILY HEATING LOAD VERSUS OUTDOOR AIR TEMPERATURE

HEATING LOAD (10^6 BTU/DAY)

OUTDOOR AIR TEMPERATURE, °F

WITH SETBACKS

WITHOUT SETBACKS
Results of DEPAB2 runs for the 400-HP boiler under the weather and operational conditions described above are summarized in figures 19 and 20, where the daily fuel consumption rate and the daily efficiency values are plotted versus the outdoor temperatures, respectively. These results were obtained from simulation of the boiler for a period of 24 hours at each weather and load condition.

Besides the overall performance values as shown in figures 19 and 20, transient performance of the boiler can also be observed from the DEPAB2 runs. For the heating load with night setbacks shown in figure 17 and the outdoor temperature being at 15°F, transient steam and stack gas temperatures of the boiler with a 6 a.m. setup are plotted versus time in figures 21 and 22, respectively; and the corresponding temperatures at a 6 p.m. setback are plotted versus time in figures 23 and 24, respectively.
FIGURE 19
DAILY FUEL CONSUMPTION VERSUS OUTDOOR AIR TEMPERATURE

FUEL CONSUMPTION (10^6 Btu/Day)

0 20 40 50 60 70
OUTDOOR AIR TEMPERATURE, °F

250
200
150
100
50
0

WITHOUT SETBACKS

WITH SETBACKS
Figure 20 Daily Fuel Utilization Efficiency Versus Outdoor Air Temperature

- Without Setbacks
- With Setbacks

Outdoor Air Temperature, °F

Daily Efficiency, %
FIGURE 21
TRANSIENT STEAM TEMPERATURE AT MORNING SETUP
(for outdoor air temperature equal to 15°F)
FIGURE 22
TRANSIENT STACK GAS TEMPERATURE AT MORNING SETUP
(OUTDOOR AIR TEMPERATURE EQUAL TO 15°F)
FIGURE 23  TRANSIENT STEAM TEMPERATURE AT NIGHT SETBACK  
(FOR OUTDOOR AIR TEMPERATURE AT 15°F)
FIGURE 24
TRANSIENT STACK GAS TEMPERATURE AT NIGHT SETBACK
(FOR OUTDOOR AIR TEMPERATURE AT 15°F)
Results from DEPAB2 runs can be used in a variety of ways. For example, results on daily fuel consumption rates (see figure 19) obtained for the example boiler under the D.C. weather and prescribed load conditions can be used to calculate the boiler seasonal performance. The first four columns of tables 1 and 2 show data read from figures 16, 18 and 19 for the boiler operating with and without setback, respectively. With these data, the boiler annual load, fuel consumption, and efficiency values can be calculated in a straightforward manner as shown in the remainders of tables 1 and 2. These resultant performance values are also shown in figure 25 for easy comparison. Reduction in annual boiler load and fuel consumption through night setbacks are seen to be 30.5% and 28.6%, respectively.
<table>
<thead>
<tr>
<th>BIN TEMP. °F</th>
<th>DAYS/BIN/yr</th>
<th>LOAD, 10^6 BTU/DAY</th>
<th>FUEL, 10^6 BTU/DAY</th>
<th>LOAD, 10^6 BTU/BIN/yr</th>
<th>FUEL, 10^6 BTU/BIN/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>8.35</td>
<td>160.90</td>
<td>192.80</td>
<td>1,343.52</td>
<td>1,609.88</td>
</tr>
<tr>
<td>25</td>
<td>20.33</td>
<td>132.40</td>
<td>158.10</td>
<td>2,691.69</td>
<td>3,214.17</td>
</tr>
<tr>
<td>35</td>
<td>46.65</td>
<td>103.50</td>
<td>123.50</td>
<td>4,828.28</td>
<td>5,761.28</td>
</tr>
<tr>
<td>45</td>
<td>43.39</td>
<td>74.19</td>
<td>91.22</td>
<td>3,219.10</td>
<td>3,958.04</td>
</tr>
<tr>
<td>55</td>
<td>26.69</td>
<td>44.60</td>
<td>57.55</td>
<td>1,190.37</td>
<td>1,526.01</td>
</tr>
<tr>
<td>65</td>
<td>15.43</td>
<td>9.22</td>
<td>17.96</td>
<td>142.26</td>
<td>277.12</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TOTAL LOAD (10^6 BTU/YEAR)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>13,415.22</td>
</tr>
<tr>
<td>TOTAL FUEL (10^6 BTU/YEAR)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>16,356.50</td>
</tr>
<tr>
<td>ANNUAL EFFICIENCY (PERCENT)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>82.02</td>
</tr>
</tbody>
</table>

**Table 1** Sample calculation of seasonal performance of a boiler with night setbacks, using results from DEPAb2 runs
<table>
<thead>
<tr>
<th>Bin Temp. °F</th>
<th>Days /Bin/Yr</th>
<th>Load, $10^6$ BTU /Day</th>
<th>Fuel, $10^6$ BTU /Day</th>
<th>Load, $10^6$ BTU /Bin/Yr</th>
<th>Fuel, $10^6$ BTU /Bin/Yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>45</td>
<td>8.35</td>
<td>229.30</td>
<td>273.12</td>
<td>1,914.66</td>
<td>2,280.55</td>
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<tr>
<td>25</td>
<td>20.33</td>
<td>189.07</td>
<td>222.62</td>
<td>3,843.79</td>
<td>4,525.86</td>
</tr>
<tr>
<td>35</td>
<td>46.65</td>
<td>148.15</td>
<td>172.63</td>
<td>6,911.20</td>
<td>8,053.19</td>
</tr>
<tr>
<td>45</td>
<td>43.39</td>
<td>106.20</td>
<td>126.96</td>
<td>4,608.02</td>
<td>5,508.79</td>
</tr>
<tr>
<td>55</td>
<td>26.69</td>
<td>63.86</td>
<td>77.45</td>
<td>1,704.42</td>
<td>2,067.14</td>
</tr>
<tr>
<td>65</td>
<td>15.43</td>
<td>21.26</td>
<td>31.99</td>
<td>328.04</td>
<td>493.61</td>
</tr>
</tbody>
</table>

**Total Load ($10^6$ BTU/Year)**

19,310.13

**Total Fuel ($10^6$ BTU/Year)**

22,929.14

**Annual Efficiency (Percent)**

84.22

**Table 2** Sample calculation of seasonal performance of a boiler without night setbacks, using results of DEPAZ2 runs
FIGURE 25  COMPARISON OF HEATING LOAD AND FUEL CONSUMPTION FOR CASES WITH AND WITHOUT SETBACKS (ON ANNUAL BASIS)
6. **SUMMARY**

A computer program DEPAB2 has been developed. DEPAB2 improves efficiency and accuracy of calculation over the original NBS-developed boiler transient analysis program DEPAB [6,7]. It adds a detailed boiler controller subroutine and combined radiative/convective and boiling/convective heat transfer subroutines necessary to accurately simulate commercial boilers. To increase calculation efficiency, thermal dynamic responses for each elementary section of the boiler is represented by a single state variable element. A commercial boiler commonly in use today can usually be analyzed by dividing it into 12 sections (although DEPAB2 allows users to choose from 3 to 62); one for the boiler furnace, ten for boiler tubes and one for the boiler shell. The solution to this 12 state variable dynamic system (with 12 differential equations and 24 algebraic equations) was found to require only 14 seconds on the EXEC-1108 CPU for each 1 real-time hour.
7. REFERENCES


APPENDIX A:

INPUT FILE #8 FOR BOILER PARAMETERS
DEPAB2 INPUT DATA CODE (FILE 8.)

Line 1 : CARB, HYDR, OXYG, XNTR, SULF

*CARB = atomic fraction of carbon in fuel, ---.
*HYDR = atomic fraction of hydrogen in fuel, ---.
*OXYG = atomic fraction of oxygen in fuel, ---.
*XNTR = atomic fraction of nitrogen in fuel, ---.
*SULF = atomic fraction of sulfur in fuel, ---.

Line 2 : HFUEL, CPFUEL, TFUEL, BTUHK

*HFUEL = fuel higher heating value, Btu/lb.
*CPFUEL = fuel specific heat at constant pressure, Btu/lb/F.
*TFUEL = fuel temperature, °F.
*BTUHK = boiler full load capacity, KBTUH.

Line 3 : ICTYPE

*ICTYPE = 1, boiler with on/off control,---.
  2, boiler with high/low/off control,---.
  3, boiler with air/fuel modulation or melting control,---.

Line 4 : TASEN, TAIR, FRGFL, EXAFL, AIROF

*TASEN = sensor time constant, minutes.
*TAAIR = time constant for decay of the off cycle air flow rate, minutes.
*FRGFL = full load fuel firing rate, lb/hr.
*EXAFL = excess air at full load (fraction),---.
*AIROF = minimum air flow rate at off cycle in fraction of the full load air flow rate, ---.

Line 5 : TBOIL(1), FRGBL(1), AIRBL(1)

IF ICTYPE =3:
*TBOIL(1) = steam temperature, F.
*FRGBL(1) = boiler firing rate in fraction of the full load firing rate, ---.
*AIRBL(1) = boiler air flow rate in fraction of the full load air flow rate, ---.

(NOT REQUIRED, IF ICTYPE=1 OR 2)

Line 6 : TBOIL(2), FRGBL(2), AIRBL(2)

SAME AS LINE 5 WITH TBOIL INCREASING.
Line 7 : TBOIL(3), FRGBL(3), AIRBL(3)
SAME AS LINE 6 WITH TBOIL INCREASING.

Line 8 : TBOIL(4), FRGBL(4), AIRBL(4)
SAME AS LINE 7 WITH TBOIL INCREASING.

Line 9 : TBOIL(4), FRGBL(4), AIRBL(4)
SAME AS LINE 8 WITH TBOIL INCREASING.

Line 10 : TBOIL(6), FRGBL(6), AIRBL(6)
IF ICTYPE = 1: NOT REQUIRED.
IF ICTYPE = 2:
*TBOIL(6) = steam temperature at which high firing turns on, F.
*FRGBL(6) = high firing rate in fraction of full firing
rate, ---.
*AIRBL:6) = air flow rate in fraction of full load air flow
rate, ---.

IF ICTYPE = 3:
SAME AS LINE 11 WITH TBOIL INCREASING.

Line 11 : TBOIL(7), FRGBL(7), AIRBL(7)

IF ICTYPE=1:
*TBOIL(7) = steam temperature at which fuel supply turns
on, F.
*FRGBL(7) = firing rate in fraction of full load firing
rate, ---.
*AIRBL(7) = air flow rate in fraction of full load air
flow rate, ---.

IF ICTYPE=2:
*TBOIL(7) = steam temperature at which high firing turns
off and low firing turns on, F.
*FRGBL(7) = low firing rate in fraction of full load firing
rate, ---.
*AIRBL(7) = air flow rate at low firing in fraction of full
load air flow rate, ---.

IF ICTYPE =3:
SAME AS LINE 10 WITH TBOIL INCREASING.
Line 12: TBOIL(8), FRGBL(8), AIRBL(8)

FOR ICTYPE = 1, 2 or 3:
* TBOIL(8) = steam temperature at which fuel supply turns off
* FRGBL(8) = FRGBL 7
* AIRBL(8) = AIRBL(7)

Line 13: WTOST, TIN, TOUT

NOT IN USE AT PRESENT, I.E.
* WTOST = any value, ---
* TIN = any value, ---
* TOUT = any value, ---

Line 14: FVOL, FSA, FCA, FRA, FDIAM, FSEM

* FVOL = furnace volume, ft$^3$
* FSA = furnace surface area, ft$^2$
* FCA = furnace air flow cross sectional area, ft$^2$
* FRA = furnace refractory area, ft$^2$
* FDIAM = furnace hydraulic diameter, ft.
* FSEM = furnace surface radiative emissivity, ---

Line 15: FNA, FNB, FNC

* FNA = $a, \beta$ and $\gamma$ in
* FMB = $Nu = a(Re)^{\beta}(Pr)^{\gamma}$
* FNC

Line 16: NT1, NT2

* NT1 = number of tube segments of the first type, ---
* NT2 = total number of tube segments, ---

Line 17: TAS(1), TVL(1), TAC(1), TDI(1), TBA(1), TBB(1), TBC(1), TBE(1)

* TAS(1) = surface area for first segment of tubes, ft$^2$
* TVL(1) = gas volume associated with first segment of tubes, ft$^3$
* TAC(1) = gas flow cross sectional area for the first segment of tubes, ft$^2$
* TDI(1) = hydraulic diameter for the first segment of tubes, ft.
* TBA(1) = a value in Nu equal to $a(Re)^{\beta}(Pr)^{\gamma}$, for the first segment of tube, ---
* TBB(1) = $\beta$ value in Nu equal to $a(Re)^{\beta}(Pr)^{\gamma}$ for the first segment of tubes, ---
\*TBC(1) = \gamma value inNu equal to \alpha(Re)^{\beta}(Pr)^{\gamma} for the first segment of tubes,---.
\*TBE(1) = radiative emissivity for the first segment of tubes,---.

Line 18: \text{TAS(NT1+1)}, \text{TVL(NT1+1)}, \text{TAC(NT1+1)}, \text{TDI(NT1+1)}, \text{TBA(NT1+1)}
\text{TBB(NT1+1)}, \text{TBC(NT1+1)}, \text{TBE(NT1+1)}

SAME AS LINE 17 BUT FOR THE \((NT1+1)\)TH SEGMENT OF TUBES.

Line 19: \text{STMVL}, \text{WTAC}, \text{WTCD}, \text{WTA}, \text{WTB}, \text{WTC}
\*STMVL = steam space volume, ft^3
\*WTAC = water flow cross sectional area, ft^2.
\*WTCD = water flow hydraulic diameter, ft
\*WTA = \alpha, \beta and \gamma value in
\*WTB = Nu equal to \alpha(Re)^{\beta}(Pr)^{\gamma}
\*WTC = for the water side heat transfer

Line 20: \text{SHARE}, \text{SHUFT}, \text{SHHGT}, \text{SHCAP}, \text{FNCAP}, \text{TBCAP}, \text{WTCAP}
\*SHARE = boiler shell surface area, ft^2.
\*SHUFT = boiler shell U-factor value, Btu/ft^2/F.
\*SHHGT = boiler shell height, ft.
\*SHCAP = boiler shell thermal capacitance, Btu/F.
\*FNCAP = furnace thermal capacitance, Btu/F.
\*TBCAP = tubes thermal capacitance, Btu/F.
\*WTCAP = water thermal capacitance, Btu/F.
APPENDIX B:

INPUT FILE #5 FOR OPERATIONAL SCHEDULES AND INITIAL CONDITIONS
DEPAB2 INPUT DATA AT TERMINAL (FILE 5.)

Line 1 : IWRITE

* IWRITE = 0, for minimum output,---.  
  1, for medium output,---.  
  2, for maximum output at debugging,---

Line 2 : NTIME

*NTIME = number of time schedules to be set minimum 
equal to 2 and maximum equal to 60,---.

Line 3 : TMIN, TIA, TOA, HDMD

*TMIN = time schedule, minutes.  
*TIA = indoor air temperature, F.  
*TOA = outdoor air temperature, F.  
*HDMD = heat demand, Btu/hr.

NOTE:  
This line is repeated NTIME times.

Line 4 : ICTYPE

*ICTYPE = 0, for continuous simulation,---  
  1, for calculating the boiler's cyclic  
  performance,---.

Line 5 : TIME, DT, IPRNT, ICALC

*TIME = starting time, minutes.  
*DT = calculation time increment, minutes.  
*IPRNT = number of DT's between successive printed  
  output,---.  
*ICALC = number of DT's to end the calculation,---.

Line 6 : ONF, TSEN, TBL

*ONF = 0., start at off cycle, ---.  
  1., start at on cycle,---  
*TSEN = sensor temperature at start, F.  
*TBL = steam temperature at start, F.
Line 7 : TSH, TRW

*TSH = boiler shell surface temperature at start, F.
*TRW = return water temperature, F.
APPENDIX C:

DEPAB2 OUTPUT DATA CODE
DEPAB2 OUTPUT DATA CODE:

TIME = time, minutes
QSUPLD = heat supplies, Btu/hr
QLOAD = heat load, Btu/hr
QFWAT = feedwater heat, Btu/hr
QSHELL = shell heat loss, Btu/hr
QEXHXT = exhaust gas sensible heat loss, Btu/hr
QLTNT = exhaust gas latent heat loss, Btu/hr
TGASFN = temperature of gas at furnace exit, °F
TGASTB = temperature of gas at tube exit, °F
TTUBFN = furnace wall temperature, °F
TTUBTB = tube wall temperature, °F
TWATER = water temperature, °F
TSENSE = sensor temperature, °F
QIPNOW = instantaneous heat input rate, Btu/hr
QU DNOW = instantaneous heat utilization rate, Btu/hr
ETANOW = instantaneous boiler efficiency value, Ratio
QIPCYC = cumulative heat input, Btu
QU DCYC = cumulative heat utilized, Btu
ETATOT = cumulative boiler efficiency, Ratio

ADDITIONAL OUTPUT FOR CYCLIC OPERATION OF BOILERS:

TIMCYC = cycling time, minutes/cycle
QU DCYC = heat utilized per cycle, Btu/cycle
QIPCYC = heat input per cycle, Btu/cycle
ETACYC = cycle efficiency, Ratio
APPENDIX D:

LISTING OF AUXILIARY SUBROUTINES
SUBROUTINE AIRPR(I, T, PATM, RH, W, CP, R, AM, AK)

*** CALCULATE AIR PROPERTIES

*** IF I=1: RELATIVE HUMIDITY GIVEN

*** IF I=2: SPECIFIC HUMIDITY GIVEN

COMMON/WRITE/1WRITE
IF (I.EQ.1) GOTO 100
P=W*PATM/(0.622+W)
100 CONTINUE
TR=T+460.
Z=1000./TR
IF (TR.GE.492.) GOTO 10
PSAT=EXP(0.03940*Z**3-0.2735*Z-10.431*Z+19.509)
GOTO 30
10 IF (TR.GE.672.) GOTO 20
PSAT=EXP(0.17829*Z**3-1.6896*Z**2-5.0988*Z+13.4353)
GOTO 30
20 PSAT=EXP(0.71692*Z**4-4.01506*Z**3+7.5568*Z**2-14.2131*Z+16.8255)
30 IF (I.EQ.1) GOTO 110
RH=P/PSAT
110 CONTINUE
IF (RH.GE.0.0000) GOTO 40
W=0.
GOTO 50
40 PW=R3*PSAT
W=0.622*PW/(PATM-PW)
50 CONTINUE
CP=0.2473786-0.4204563E-04*TR+0.5767857E-07*TR**2
% -0.1493036E-19*TR**3
CP=CP*+0.444*W)/(1.00+V)
R=(53.34+85.76*W)/(1.00+V)
AM=5.5629E-03+8.7157E-05*TR-2.9464E-08*TR**2
% +6.250E-12*TR**3
AK=-2.835E-04+3.263E-05*TR-8.253E-09*TR*TR
% +1.239E-12*TR**3
IF (IWRITE.LE.1) GOTO 700
WRITE(6,701) T, PATH, RH, W, CP, R, AM, AK
% 7X, 'R', 8X, 'AM', 7X, 'AK' /8(1PE9.1))
700 CONTINUE
RETURN
END
SUBROUTINE H2OLQ(T, RO, CP, AK, AM, ST, BT)

*** CALCULATE WATER PROPERTIES

DIMENSION X(5), A(5,6), B(6), C(6)

INPUT DATA:

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>T</td>
<td>TEMPERATURE</td>
<td>F</td>
</tr>
<tr>
<td>A(I,1), I=1,5</td>
<td>DENSITY</td>
<td>LB/CFUT</td>
</tr>
<tr>
<td>A(I,2), I=1,5</td>
<td>SPECIFIC HEAT</td>
<td>BTU/LB/F</td>
</tr>
<tr>
<td>A(I,3), I=1,5</td>
<td>THERMAL CONDUCTIVITY</td>
<td>BTU/FT-HR-F</td>
</tr>
<tr>
<td>A(I,4), I=1,5</td>
<td>DYNAMIC VISCOSITY</td>
<td>LB/FT-HR</td>
</tr>
<tr>
<td>A(I,5), I=1,5</td>
<td>SURFACE TENSION</td>
<td>LB/FT</td>
</tr>
<tr>
<td>A(I,6), I=1,5</td>
<td>EXPANSION COEFFICIENT</td>
<td>1/R</td>
</tr>
</tbody>
</table>

OUTPUT DATA:

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<tbody>
<tr>
<td>RO</td>
<td>DENSITY</td>
<td>LB/CFUT</td>
</tr>
<tr>
<td>CP</td>
<td>SPECIFIC HEAT</td>
<td>BTU/LB-F</td>
</tr>
<tr>
<td>AK</td>
<td>THERMAL CONDUCTIVITY</td>
<td>BTU/FT-HR-F</td>
</tr>
<tr>
<td>AM</td>
<td>DYNAMIC VISCOSITY</td>
<td>LB/FT-HR</td>
</tr>
<tr>
<td>ST</td>
<td>SURFACE TENSION</td>
<td>LB/FT</td>
</tr>
<tr>
<td>BT</td>
<td>EXPANSION COEFFICIENT</td>
<td>1/R</td>
</tr>
</tbody>
</table>

DATA NP/5/
DATA X/32.,60.,100.,200.,500./
DATA A/62.4,62.3,62.0,60.0,1.49/9
%1.01,1.00,1.00,1.19,0.319,0.340,0.364,0.394,0.349,
%4.33,2.71,1.65,0.74,0.26,4.18E-03,3.97E-03,3.67E-03,
%2.94E-03,1.18E-03,-4.E-5,8.E-5,2.E-4,4.E-4,1.E-3/
DO100J=1,6
DO100I=1,5
B(I)=A(I,J)
C(J)=TAB1(NP,X,B,T)
100 CONTINUE
RO=C(1)
CP=C(2)
AK=C(3)
AM=C(4)
ST=C(5)
BT=C(6)
RETURN
END
SUBROUTINE H20VP(T, RO, CP, AK, AM, HFG, BT)

*** CALCULATE STEAM PROPERTIES

DIMENSION X(5), A(5, 6), B(6), C(6)

INPUT DATA:

*** CALCULATE STEAM PROPERTIES

INPUT DATA:

<table>
<thead>
<tr>
<th>T</th>
<th>TEMPERATURE</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>X(I), I=1,5</td>
<td>T, INDEPENDENT VARIABLE</td>
<td>F</td>
</tr>
<tr>
<td>A(I, 1), I=1,5</td>
<td>DENSITY</td>
<td>LB/CUFT</td>
</tr>
<tr>
<td>A(I, 2), I=1,5</td>
<td>SPECIFIC HEAT</td>
<td>BTU/LB/F</td>
</tr>
<tr>
<td>A(I, 3), I=1,5</td>
<td>THERMAL CONDUCTIVITY</td>
<td>BTU/FT-HR-F</td>
</tr>
<tr>
<td>A(I, 4), I=1,5</td>
<td>DYNAMIC VISCOSITY</td>
<td>LB/FT-HR</td>
</tr>
<tr>
<td>A(I, 5), I=1,5</td>
<td>HEAT OF VAPORIZATION</td>
<td>BTU/LB</td>
</tr>
<tr>
<td>A(I, 6), I=1,5</td>
<td>EXPANSION COEFFICIENT</td>
<td>1/R</td>
</tr>
</tbody>
</table>

OUTPUT DATA:

| RO | DENSITY | LB/CUFT |
| CP | SPECIFIC HEAT | BTU/LB-F |
| AK | THERMAL CONDUCTIVITY | BTU/FT-HR-F |
| AM | DYNAMIC VISCOSITY | LB/FT-HR |
| HFG | HEAT OF VAPORIZATION | BTU/LB |
| BT | EXPANSION COEFFICIENT | 1/R |

DATA NP/5/
DATA X/32., 100., 200., 300., 400. /
DATA A/3.03E-4, 2.85E-3, 2.97E-2, 0.155, 1.48, 0.44, 0.4488, 0.4751, 0.5508, 0.968, 0.01, 0.0116, 0.0140, 0.0172, 0.0306, 0.0192, 0.0229, 0.0283, 0.0301, 0.0427, 0.1075, 0.1037, 0.1977, 0.910, 0.714, 0.32, 0.32E-3, 1.79E-3, 1.32E-3, 1.316E-3, 1.042E-3/ D0100 J=1,6 D0100 I=1,5 B(I)=A(I, J) C(J)=TAB1(NP, X, B, T)

100 CONTINUE
RO=C(1)
CP=C(2)
AK=C(3)
AM=C(4)
HFG=C(5)
BT=C(6)
RETURN
END
SUBROUTINE PRDP3(T,PC02,PH20,P02,PN2,PS02, XAMK,AKK)

*** CALCULATE VISCOSITY AND CONDUCTIVITY OF PRODUCTS

DIMENSION X(11),A(11),B(11),AM(5),AK(5)
DATA X/\-10.,260.,440.,620.,800.,1070.,
%1200.,2420.,3140.,3500.,4160./
DATA A/0.0337,0.0333,0.0646,0.073,0.0806,0.0911,
%0.1062,0.1329,0.1590,0.1590,0.1710/
DATA B/0.01287,0.01944,0.02333,0.02692,0.03022,
%0.03433,0.04173,0.05348,0.0612,0.0646,0.0709/
DATA AM/0.869,0.685,1.123,0.964,0.889/
DATA AK/0.925,0.906,1.037,0.983,0.925/
NP=11
AMM=PC02*AM(1)+PH20*AM(2)+P02*AM(3)+
%PN2*AM(4)+PS02*AM(5)
AKK=PC02*AK(1)+PH20*AK(2)+P02*AK(3)+
%PN2*AK(4)+PS02*AK(5)
AMM=AMM*TAB1(NP,X,A,T)
AKK=AKK*TAB1(NP,X,B,T)
RETURN
END
FUNCTION CPF(T1, T2, PC02, PB20, P02, PS02, PN2)

*** INPUT: (T1) TEMPERATURE, DEC R, (T2)
C TEMPERATURE, DEC R, (PC02) NO. MOLES CO2,
C (PB20) NO. MOLES H2O, (P02) NO. MOLES O2,
C (PS02) NO. MOLES SO2, (PN2) NO. MOLES N2

*** OUTPUT: (CP) SPECIFIC HEAT OF PROD,
C BTU/LB-DEC R
C WHERE CPF IS THE SPECIFIC HEAT FUNCTION

C DIMENSION C(6,2)
DIMENSION A(30), AA(30), BB(30)
%9.510155E-12, 2.1701, 1.0378115E-2, -1.0739308E-5, 6.3459175E-9, -1.628
%0.791E-12, 4.1555916, -1.7244334E-3, 5.6982316E-6, -4.5930444E-9, 9.14233
%654E-12, 3.691648, -1.3332552E-3, 2.65031E-6, -9.768834E-10, -9.977223
%4E-14, 3.719946E-2, 5.1672885E-3, 3.8537353E-6, -8.2998716E-9, 2.708218E
%12, 3.2357132, 5.6551207E-3, -2.497028E-7, -4.2206766E-9, 2.1392733E-
%12/
DATA B/1.1795744, 1.0950594E-2, -4.062213E-6, 7.1370281E-10,
%4.7490335E-14, 4.4129266, 3.1922896E-3, -1.297823E-5, 2.4147446E-10
%1.6742998E-14, 2.6797532, 3.0317118E-3, -8.355187E-7, 1.790883E-10,
%6.197356E-15, 2.8545761, 1.5976316E-3, -6.2566254E-7, 1.315849E-
%10, -7.687907E-13, 3.5976129, 7.8145603E-4, -2.238667E-7, 4.2499159E-
%11, -3.346024E-15, 5.1982451, 2.0595095E-3, -8.6254450E-7,
%1.6636523E-10, -1.1847838E-14/

*** MODIFY A AND B FROM K UNITS TO R UNITS

DO 10 I=1, 6
  M=5*(I-1)
  DO 10 J=1, 5
    JJ=M-J
    AA(JJ)=A(JJ)/(1.8**(J-1))
    BB(JJ)=B(JJ)/(1.8**(J-1))
  CONTINUE

*** DETERMINE TEMP RANGE OF T1 AND T2

IF(T1.GT.1800.)GO TO 25
IF(T2.GT.1800.)GO TO 15

*** T1 AND T2 ARE LESS THAN 1800 R

DO 20 I=1, 6
  C(I,1)=0.
  DO 30 J=1, 6
    M=5*(I-1)
    DO 35 J=1, 5
      JJ=M-J
      C(I,1)=C(I,1)+AA(JJ)*(T2**J-T1**J)/J
    CONTINUE
  C(I,1)=C(I,1)*1.98726/(T2-T1)
  CONTINUE

CPF=(PC02*C(2,1)+PB20*C(3,1)+PN2*C(4,1)
  1-P02*C(5,1)+PS02*C(6,1))/(PC02*44.
  *PB20*18. +PN2*28.+P02*32. +PS02*64.)
GO TO 99
C 15 CONTINUE
C *** T1 IS LESS THAN 1800 R AND T2 IS
C GREATER THAN 1800 R
C
TM=1800.
DO 22 I=1,6
DO 22 J=1,2
22 C(I,J)=0.
DO 32 I=1,6
M=5*(I-1)
DO 37 J=1,5
J=J+M
C(I,1)=C(I,1)+AA(J)*(TM**J-T1**J)/J
C(I,2)=C(I,2)+BB(J)*(T2**J-TM**J)/J
37 CONTINUE
C(I,1)=(C(I,1)+C(I,2))*1.98726/(T2-T1)
32 CONTINUE
CPF=(PC02*C(2,1)+PH20*C(3,1)+PN2*C(4,1)+
%+P02*C(5,1)+PS02*C(6,1))/(PC02+44.
%+PH20*18.+PN2*28.+P02*32.+PS02*64.)
GO TO 99

C 25 CONTINUE
IF(T2.LT.1800.)GO TO 53

C *** T1 AND T2 ARE GREATER THAN 1800 R
C
TM=1800.
DO 21 I=1,6
DO 21 J=1,2
21 C(I,J)=0.
DO 30 I=1,6
M=5*(I-1)
DO 35 J=1,5
J=J+M
C(I,2)=C(I,2)+BB(J)*(T2**J-T1**J)/J
35 CONTINUE
C(I,2)=C(I,2)*1.98726/(T2-T1)
30 CONTINUE
CPF=(PC02*C(2,1)+PH20*C(3,1)+PN2*C(4,1)+
%+P02*C(5,1)+PS02*C(6,1))/(PC02+44.
%+PH20*18.+PN2*28.+P02*32.+PS02*64.)
GO TO 99

C 55 CONTINUE
C *** T1 IS GREATER THAN 1800 R AND T2
C IS LESS THAN 1800 R
C
TM=1800.
DO 24 I=1,6
DO 24 J=1,2
24 C(I,J)=0.
DO 34 I=1,6
M=5*(I-1)
DO 39 J=1,5
J=J+M
C(I,1)=C(I,1)+AA(J)*(TM**J-T2**J)/J
C(I,2)=C(I,2)+BB(J)*(T1**J-TM**J)/J
39 CONTINUE
C(I,1)=(C(I,1)+C(I,2))*1.98726/(T1-T2)
34 CONTINUE
CPF=(PC02*C(2,1)+PH20*C(3,1)+PN2*C(4,1)+
%+P02*C(5,1)+PS02*C(6,1))/(PC02+44.
%+PH20*18.+PN2*28.+P02*32.+PS02*64.)

C 99 CONTINUE
RETURN
END
SUBROUTINE PP(PTOTAL, CARB, HYDR, OXYG, XNTR, SULF, EXAIR,
*PC02, PH20, PS02, PO2, PN2, RATF, RPTF, RWTF)

C *** INPUT: (CARB) No. MOLES Carbon, (HYDR) No. MOLES
C Hydrogen, (OXYG) No. MOLES Oxygen, (XNTR) No. MOLES
C Nitrogen, (SULF) No. MOLES Sulfur, (EXAIR) Excess Air

C *** OUTPUT: (PC02) Partial Pres CO2, ATM, (PH20)
C Partial Pres H20, ATM, (AFRTT) Theoretical Air Fuel
C Ratio, (PC02) No. MOLES CO2, (PH20) No. MOLES H20, (PO2)
C No. MOLES O2, (PS02) No. MOLES SO2, (PN2) No. MOLES N2,
C (UPRD) Unit Partial Pres of Products, LB Prod/LB Fuel

C *** Moles of O and N Reqd to Be Added
R00=2.*CARB+0.5*HYDR+2.*SULF-OXYG
RN0=3.76*R00

C *** Moles of CO2, H2O, O2, S02 and N2 in Products
PC02=CARB
PH20=0.5*HYDR
PO2=0.5*R00*EXAIR
PS02=SULF
PN2=0.5*XNTR+0.5*RN0*(1.+EXAIR)

C *** WT of Fuel, Air and Products
WTF=12.*CARB+HYDR+16.*OXYG+14.*XNTR+32.*SULF
WTA=(16.*RN0+14.*RN0)*(1.+EXAIR)
WTP=(44.*PC02+18.*PH20+32.*PO2+64.*PS02+28.*PN2)
WTV=18.*PH20

C *** Compute PPC02, PH20, AFRTT and UPRD
AMULT=PTOTAL/(PC02+PH20+PO2+PS02+PN2)
PC02=PC02*AMULT
PH20=PH20*AMULT
PS02=PS02*AMULT
PO2=PO2*AMULT
PN2=PN2*AMULT
RATF=WTA/WTF
RPTF=WTP/WTF
RWTF=WTV/WTF

C RETURN
END

-74-
FUNCTION TAFF(HHV, RWTF, UPRD, PC02, PH20, P02, PS02, PN2, CP1, T0, PC, CP)

C

C *** INPUT: (HHV) HIGHER HTG VALUE, BTU/LB FUEL,
C (UPRD) UNIT PARTIAL PRES OF PROD, LB PROD/
C LB FUEL. (PC02) NO. MOLES CO2, (PH20) NO. MOLES
C H2O, (P02) NO. MOLES O2. (PS02) NO. MOLES S02,
C (PN2) NO. MOLES N2. (CP1) INITIAL GUESS OF SPECIF HT OF PROD.
C BTU/LB-DEG R. (T0) BASE TEMP, DEG R, (PC) PERCENT CHANGE
C IN ACCURACY REQD BETWEEN TWO SUCCESSIVE VALUES OF TAF
C
C *** OUTPUT: (TAF) ADIABATIC FLAME TEMP, DEG R,
C WHERE TAFF IS THE ADIABATIC FLAME TEMP FUNCTION
C

HHV=HHV - 1050. *RWTF
TAF1=HHV/UPRD/CP1+T0
6 CP=CPF(TAF1, T0, PC02, PH20, P02, PS02, PN2)
TAF2=HHV/UPRD/CP+T0
T=ABS((TAF1-TAF2)/TAF1)
TAF1=TAF2
IF(T.GT.PC)GO TO 6
TAFF =TAF1

C
RETURN
END
SUBROUTINE CP(BTUHK, HFUEL, CPFUEL, TFUEL, TAIR, RATF, RPTF, WFUEL, WAIR, WGAS)

*** CALCULATE BOILER FUEL/AIR FLOW

INPUT DATA:
- BTUHK: BTUH INPUT RATE
- HFUEL: FUEL HEATING VALUE, BTU/LB
- CPFUEL: FUEL SPECIFIC HEAT, BTU/LB/F
- RATF: MASS RATIO OF AIR TO FUEL, ---
- RPTF: MASS RATIO OF PRODUCT TO FUEL, ---
- TFUEL: FUEL TEMPERATURE, F
- TAIR: AIR TEMPERATURE, F

OUTPUT DATA:
- WFUEL: FUEL FLOW RATE, LB/HR
- WAIR: AIR FLOW RATE, LB/HR
- WGAS: TOTAL GAS FLOW RATE, LB/HR

COMMON/WRITE/IWRITE
IF(IWRITE.EQ.2) WRITE(6,702) BTUHK, HFUEL, CPFUEL, RATF, RPTF
702 FORMAT(/2X,3GF:12X,5HBTUHK,6X,5HHFUEL,
%6X,5HCPFUEL,5X,4HRATF,7X,4HRPTF/5(1PE11.3))
HHV=HFUEL+CPFUEL*(TFUEL-TAIR)
WFUEL=1000.0*BTUHK/HFUEL
WAIR=RATF*WFUEL
WGAS=RPTF*WFUEL
WRITE(6,710) TFUEL, TAIR, WFUEL, WAIR, WGAS
710 FORMAT(2X,5HHTFUEL,6X,4HTAIR,7X,5HWFWUEL,6X,4HWAIR,7X,4HWGAS/ 
%5(1PE11.3))
RETURN
END
SUBROUTINE BG(BTUHK, EXAIR, HFUEL, CPFUEL, XTFUEL, THAIR, WFUEL, WAIR)

C *** BOILER AIR, FUEL AND KBTUH INPUT
C
IF(WFUEL.GT.0.0001) GOTO100
BTUHK=0.
EXAIR=0.
GOTO200

100 BTUHK=0.001*WFUEL*(HFUEL+CPFUEL*(TFUEL-77.))
RATIO=WAIR/WFUEL
CBAIR=RATIO/THAIR
EXAIR=CBAIR-1.

200 RETURN

END
```fortran
FUNCTION RENB(AMAS, AMU, AC, D)

*** CALCULATE REYNOLDS NUMBER

COMMON/WRITE/IWRITE
IF(IWRITE.LE.1)GOTO704
WRITE(6,706)AMAS,AMU,AC,D
704 CONTINUE
706 FORMAT(/2X,5HRENB:/2X,4HAMAS,7X,3HAMU,8X,2HAC,9X,
%1HD/4(1PE11.3))
G=AMAS/AC
RENB=G*D/AMU
IF(IWRITE.LE.1)GOTO700
WRITE(6,702)RENB
700 RETURN
702 FORMAT(/2X,5HRENB=,1PE11.3)
END
```
FUNCTION PRNB(AMU, CP, AK)

*** CALCULATE PRANDTL NUMBER.

COMMON WRITE IWRITE
IF (IWRITE .LE. 1) GOTO 704
WRITE (6, 706) AMU, CP, AK
704 CONTINUE
706 FORMAT (/2X, 5HPRNB=, /2X, 3HAMU, 8X, 2HCP, 9X, 2HAK/ 
%3(1PE11.3))
PRNB = AMU*CP/AK
 IF (IWRITE .LE. 1) GOTO 700
WRITE (6, 702) PRNB
700 RETURN
702 FORMAT (/2X, 5HPRNB=, 1PE11.3)
END
FUNCTION AIRFHT(T1, T2, AL)

*** CALCULATE AIRSIDE FREE CONVECTION HEAT TRANSFER COEFFICIENT

INPUT DATA:
T1      SURFACE TEMPERATURE  F
T2      AIR TEMPERATURE        F
AL      CHARACTERISTIC LENGTH  FT

OUTPUT DATA:
AIRFHT  AIR FREE CONVECTION HT TRANSFER COEFF  BTU/SQFT-HR-F

DT=ABS(T1-T2)
GG=(AL**3)*AL
IF(GG.GT.1.E3)GOTO100
AIRFHT=0.29*(DT/AL)**0.25
GOTO200
100 AIRFHT=0.21*(DT**0.3333)
200 RETURN
END
FUNCTION GEF(PPC02, PPH20, XL, TG)
C
*** INPUT: (PPC02) PARTIAL PRES CO2, ATM. (PPH20)
C PARTIAL PRES H20, ATM. (XL) LENGTH OF COMBUSTION
C CHAMBER, FT, (TG) RADIATING GAS TEMP, DEG R
C
*** OUTPUT: (CE) GAS EMISSIVITY
C WHERE GEF IS THE GAS EMISSIVITY FUNCTION
C
*** SELECT GAS EMISSIVITY CONSTANTS
C C1 AND C2
C
XX=(PPC02+PPH20)*XL
IF(XX.GT..2)GO TO 4
C1=406.9
C2=0.62
GO TO 6
4 C1=237.
C2=0.4
6 CONTINUE
C
*** COMPUTE GAS EMISSIVITY
C
GEF=XX**C2*C1/TG
C
RETURN
END
FUNCTION GS(AT, CS, GE, SE)

C *** CALCULATE GAS/SINK EXCHANGE AREA

C GS=1./SE+1./(CS*GE)-1.
CS=AT/GS
RETURN
END
FUNCTION OVHT(I, AO, AP, AF, AI, ALFO, ALFI, TP, AK, FEE)

*** CALCULATE OVERALL HEAT TRANSFER COEFFICIENT

I = 1: OUTSIDE SURFACE

I = 2: INSIDE SURFACE

I = 3: OVERALL

COMMON/WRITE/IWRITE

IF(IWRITE.LE.1) GOTO 704

WRITE(6, 706) I, AO, AP, AF, AI, ALFO, ALFI, TP, AK, FEE

CONTINUE

706 FORMAT(/2X, 5HOVHT=, 2X, 1I1, 2X, 2HAO, 9X, 2HAP, 9X, 2HAF, 9X, %2HAI/13, 4(1PE11.3)/2X, 4HALFO, 7X, 4HALFI, 7X, 2HTP, 9X, %2HAK, 9X, 3HFEE/=5(1PE11.3))

AA = AO*TP/(AP*AK)

IF(I.EQ.2) GOTO 10

ALF = AO/(ALFO*(AO-AF*(1.-FEE)))

ALF = ALF + 0.5*AA

IF(I.EQ.1) GOTO 100

ALF = ALF + 0.3*AA + AO/(AI*ALFI)

GOTO 100

10 ALF = AI*TP/(2.*AP*AK) + 1./ALFI

GOTO 100

100 OVHT = 1./ALF

IF(IWRITE.LE.1) GOTO 700

WRITE(6, 702) OVHT

RETURN

700 FORMAT(/2X, 5HOVHT=, 1PE11.3)

END
FUNCTION TAB1(NP, X, Y, XI)
C
C *** PURPOSE: FROM TABULATED Y VS X VALUES
C TO DETERMINE Y(XI) VALUE
C
C *** WRITTEN BY: JOSEPH CHI 00FEB20
C
C *** INPUT/OUTPUT LIST:
C
NP  NUMBER OF DATA POINTS
X  DATA POINT INDEPENDENT VARIABLES
Y  DATA POINT DEPENDENT VARIABLES
TAB1  OUTPUT DEPENDENT VARIABLE
XI  INPUT INDEPENDENT VARIABLE
C
DIMENSION X(NP), Y(NP)
C
C *** SET OUT OF RANGE Y1(XI) VALUES
XMIN=X(1)
XMAX=X(NP)
IF(XI.GT.XMIN) GOTO10
Y1=Y(1)
GOTO100
10 IF(XI.LT.XMAX) GOTO20
Y1=Y(NP)
GOTO100
C
C *** INTERPOLATE FOR Y1(XI) VALUE
20 I=1
40 IF (XI.GT.X(I)) GOTO30
DXT=X(I)-XI-1
DYT=Y(I)-Y(I-1)
RDXT=1./DXT
DYODX=DYT*RDXT
DX=XI-X(I-1)
Y1=Y(I-1)+DX*DYODX
GOTO100
30 I=I+1
GOTO40
100 TAB1=Y1
RETURN
END
FUNCTION STSATT(PG)

C
CALCULATE STEAM SATURATION T FROM P

C
DATA AC, BC, CC, DC, EG, FG, AA, BB, TFR/90. 41858,
+16041.139, -10.48695, 0.0946831, 0.270452,
+1179.51, 132., 570., 459.67/
IF(PG LE. 9) GOTO999
PLOG=ALOG(PG)
TR=0.4342948*AA*PLOG+BB
D010 ITR=1,30
TR0=TR
C=ALOG(ABS(FG-TR0))
F=AC+BC/TRO+CG*ALOG(TRO)+DG*TRO+EG=(FG-TR0)*C/TR0)-PLOG
FTs=-BC/TRO**2+CC/TRO+DC
IF(ABS(EG) GE. 1.E-20) FT=FT-EG*(1./TRO+FC*C/TR0**2)
TR=TR0-F/FT
IF(ABS(TR-TR0) LE. 0.05) GOTO20
10 CONTINUE
999 WRITE(6,100)
100 FORMAT(5X,'ERROR IN CALLING STSATT-')
RETURN
20 STSATT=TR-TFR
RETURN
END
SUBROUTINE ROGT?(ROG, TC, PG)

CALCULATE T AND P FROM SATURATION VAPOR DENSITY

DIMENSION RO(21), T(21)
DATA RO/0.00058679, 0.00285714, 0.01031034, 0.01992032,
+0.02973536, 0.03731343, 0.04319634, 0.05158362, 0.06124824,
+0.0722273, 0.08497621, 0.11560694, 0.15451174, 0.20329335,
+0.26371366, 0.33772374, 0.42753313, 0.53587697, 0.90818273,
+1.4790711, 3.7353248/
DATA T/50., 100., 150., 180., 200., 212., 220., 230., 240.,
+250., 260., 280., 300., 320., 340., 360., 380., 400.,
+450., 500., 600. /
NP=21
TC=TAB1(NP, RO, T, ROG)
PG=STSATP(TC)
RETURN
END
FUNCTION STSATP(TG)

CALCULATE STEAM SATURATION PRESSURE FROM TEMPERATURE

DATA AC, BC, CC, DG, EC, FG, EEP, TC, TFR/90.41858,
+16041.139, -10.48695, 0.6946831, 0.270452,
+1179.51, 2.7182818, 1165.11, 459.67/
T = TG + TFR
IF(T.CT. TC) GOTO999
A = ALGC(ABS(FG-T))
STSATP = EEP**(AC+BC/T+CG*Aalog(T)+DG*T+EC*C*((FG-T)/T))
RETURN

999 WRITE(6,100)
100 FORMAT(5X,'ERROR IN CALLING -STSATP- ')
RETURN
END
FUNCTION SGDP(AMAS, V, RE, AF, BF, D, AC, AL)

*** CALCULATES SINGLE-PHASE PRESSURE DROP

COMMON/ WRITE/ IWRITE
IF(IWRITE. LE. 1) GOTO 704
WRITE(6, 706) AMAS, V, RE, AF, BF, D, AC, AL
704 CONTINUE
706 FORMAT(/2X, 5HSGDP:/2X, 4HAMAS, 7X, 1HV, 10X, 2HRE, 9X, 2HAF/4(1PE11.3)/2X, 2HBF, 9X, 1HD, 10X, 2HAC, 9X, 2HAL/
*/2X, AAT=0.046
*/2X, BBT=0.1
*/2X, AAL=16.
*/2X, BBL=1
*/2X, G=AMAS/AC
*/2X, TALF=AF
*/2X, TBLF=BF
IF (TALF.GT.0.00005) GOTO 10
IF (RE.GT.2000.) GOTO 20
TALF=AAL
TBLF=-BBL
GOTO 10
20 TALF=AAT
TBLF=-BBT
10 F=TALF*RE**TBLF
SGDP=(3.33333E-11)*F*V*AL*C*D
IF(IWRITE. LE. 1) GOTO 700
WRITE(6, 702) SGDP
700 RETURN
702 FORMAT(/2X, 5HSGDP=,1PE11.3)
END
SUBROUTINE WATPR(TW, WATRO, WATK, WATM, WATHFG, WATCP)

*** CALCULATE WATER PROPERTIES

COMMON /WRITE/IWRITE
DIMENSION ARO(3), AK(5), AM(5), AEFG(3)
DATA ARO/0.11647E03, 0.40054E00, 0.10815E-02, 
%0.12387E-05, 0.49002E-09/
DATA AK/-0.27694E00, 0.45215E-03, 0.49008E-05, 
%0.8643E-08, 0.41387E-11/
DATA AM/0.79424E03, -0.47589E01, 0.10622E-01, 
%0.10466E-04, 0.37690E-06/
DATA AEFG/3.514E04, -0.13714E02, 0.35945E-01, 
%0.43525E-04, 0.19695E-07/
IF (IWRITE.LE.1) GOTO706
WRITE(6,710) TW
706 CONTINUE
710 FORMAT(/2X,9HWATPR: TW=, 1PE11.3)
TFR=439.67
TW=TW+TFR
WATRO=0.
WATK=0.
WATM=0.
WATHFG=0.
IF (TW.LE.32.) GOTO100
DO10 I=1,5
J=I-1
AA=TWR**J
WATRO=WATRO+ARO(I)*AA
WATK=WATK+AK(I)*AA
WATM=WATM+AM(I)*AA
WATHFG=WATHFG+AEFG(I)*AA
10 WATCP=1.
GOTO200
100 WATRO=19.
WATK=0.82
WATM=1.25
WATHFG=1219.
WATCP=0.46
200 IF (IWRITE.LE.1) GOTO706
WRITE(6,702) TW, WATRO, WATK, WATM, WATHFG, WATCP
700 RETURN
702 FORMAT(2X, 2HTW, 9X, 5HWATRO, 6X, 4HWATK, 7X, 
%4HWATM, 7X, 5HWATHFG, 5X, 5HWATCP/6(1PE11.3))
END
A COMMERCIAL HEATING BOILER TRANSIENT ANALYSIS SIMULATION MODEL (DEPAB2)

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Document describes a computer program; SF-185, FIPS Software Summary, is attached.

This report documents a second generation boiler transient analysis computer program DEPAB2. It treats in detail the boiler controllers and different modes of heat transfer (which include conductive, convective and radiative) in the boiler environment; and it is built upon 7 principal subroutines for the controller and interface flux calculations and 16 auxiliary subroutines for fluid properties, fuel/air combustion and heat transfer parameters.

Also included is a guide on using DEPAB2. Included are:
1. Input data requirements for DEPAB2 runs,
2. Procedures for DEPAB2 runs, and
3. Output data interpretation.

In addition, a worked example is described and discussed in detail to illustrate:
1. the DEPAB2 runs, (2) quantitative information generated by DEPAB2 runs, and (3) use of information from DEPAB2 runs to design energy conservation strategies.

Boilers; computer model; energy conservation; fire tube boilers; heat transfer

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