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A Commercial Heating Boiler Transient Analysis Simulation Model (DEPAB2)

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A COMMERCIAL HEATING BOILER TRANSIENT ANALYSIS SIMULATION MODEL (DEPAB2)

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U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, *Secretary*
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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.

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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.

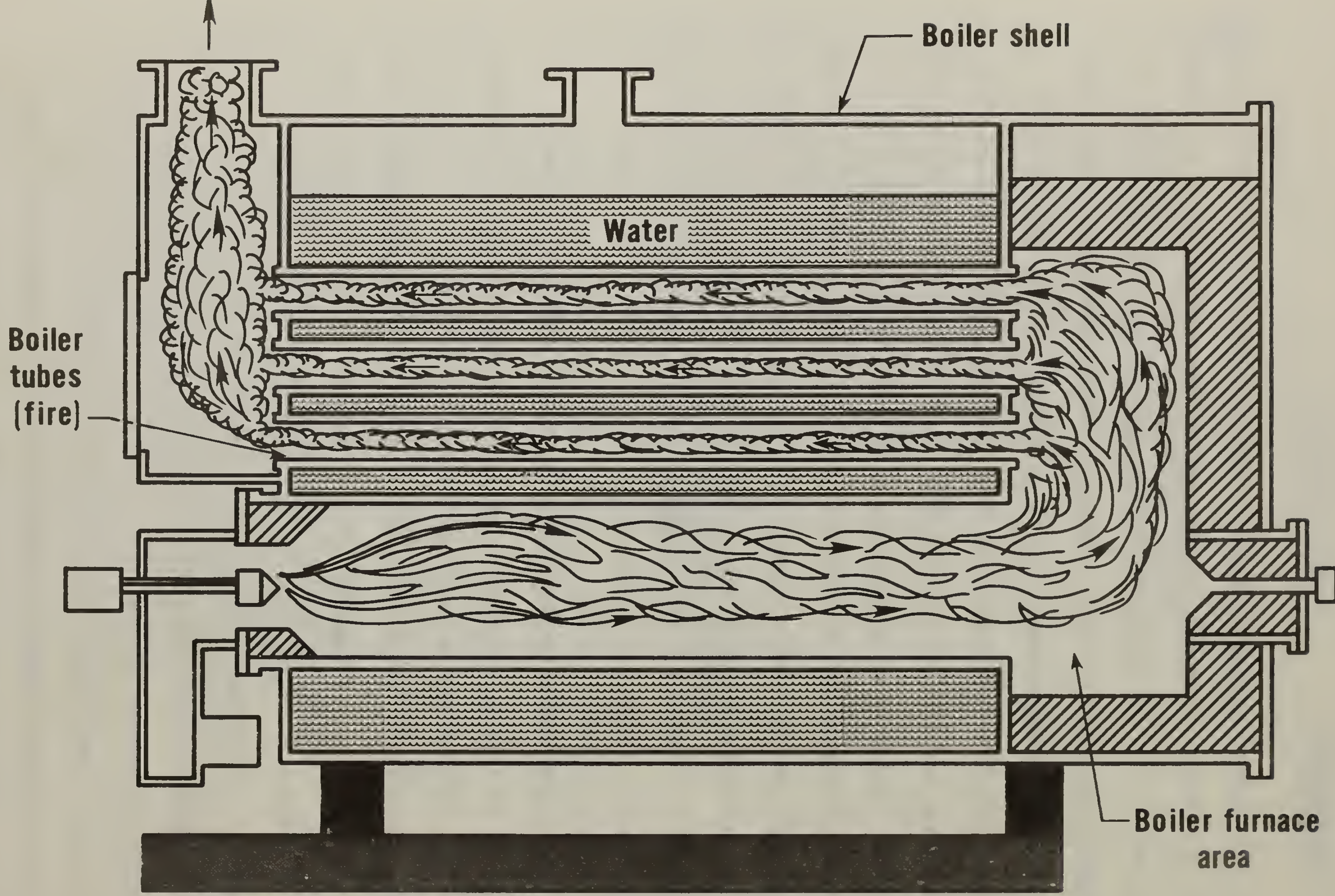


Figure 1. Typical Fire Tube Boiler (Two Pass)

2. BOILER CONTROLLER DYNAMICS AND SUBROUTINE CT

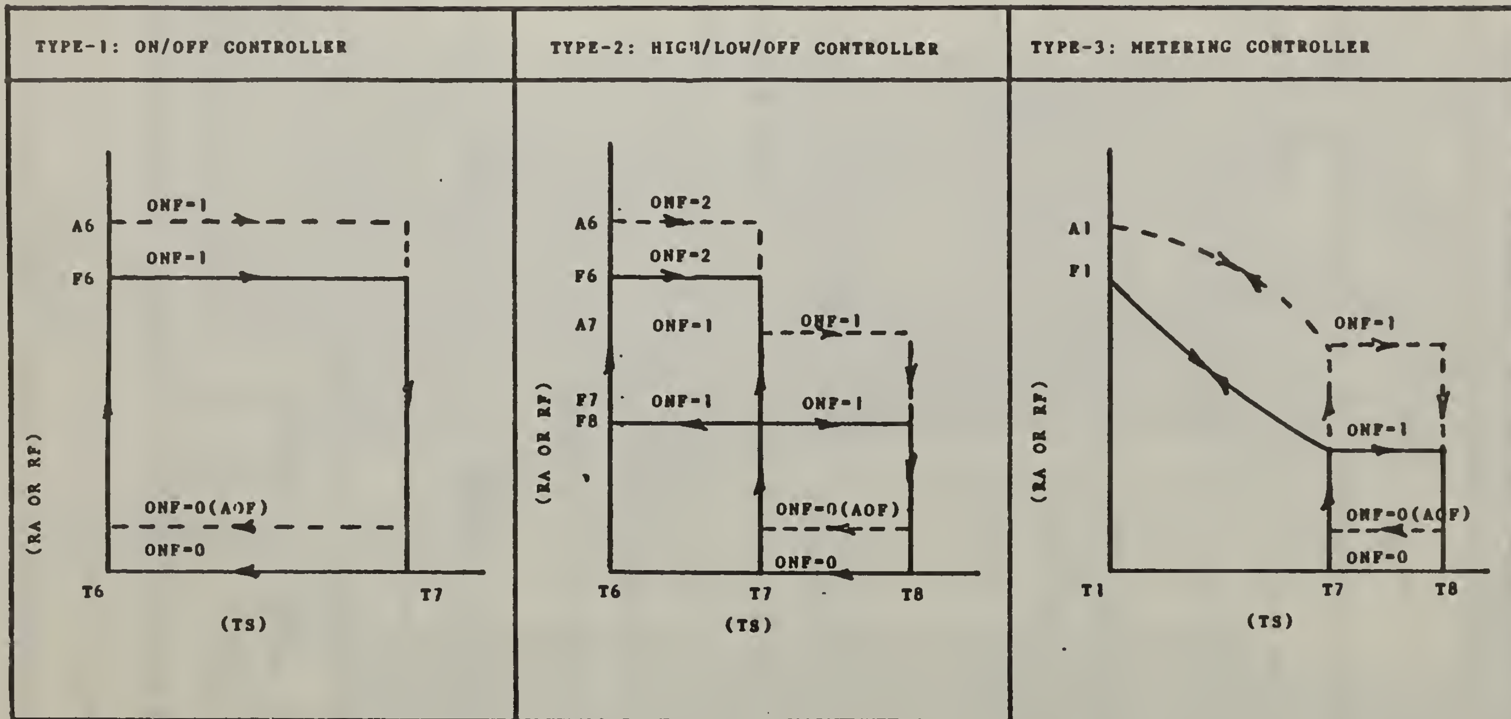
There are five types of combustion controllers which are in common use for commercial heating boilers today [1]. These controllers have three basic logics as shown in figure 2. These three basic logics are represented by: (1) the on/off controller, (2) the high/low/off controller, and (3) the air/fuel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



KEYS:
T1,T2,......SENSOR TEMPERATURE(TS);
A1,T2,......AIR FLOW RATE (RA);
F1,F2,......FUEL FLOW RATE (RF);

AOF OFF CYCLE STEADY STATE AIR FLOW RATE
ONF CONTROL STATUS
---, AIR SCHEDULE; ——, FUEL SCHEDULE

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:

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

where w is the instantaneous air or fuel flow rate; τ 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,
     *TBL,ICTYPE,TASEN,TAAIR,AIROF,DT)
C
C     CALCULATE CONTROLLER STATUS
C
      COMMON/CONTRL/TBOIL(8),FRGBL(8),AIRBL(8)
      COMMON/WRITE/IWRITE
      TSEN=TSEN+(DT/TASEN)*(TBL-TSEN)
      GOTO(100,200,300),ICTYPE
100   IF(ONF.GT.0.5.AND.TSEN.GE.TBOIL(7))GOTO110
      IF(ONF.LT.0.5.AND.TSEN.LE.TBOIL(6))GOTO120
      GOTO500
110   ONF=0.
      GOTO500
120   ONF=1.
      WFUEL=FRGBL(6)
      WAIR=AIRBL(6)
      GOTO600
200   IF(ONF.LT.0.5)GOTO210
      IF(ONF.GT.0.5.AND.ONF.LT.1.5)GOTO220
      IF(ONF.GT.1.5)GOTO230
210   IF(TSEN.GT.TBOIL(7))GOTO500
      ONF=1.
      WFUEL=FRGBL(7)
      WAIR=AIRBL(7)
      GOTO600
220   IF(TSEN.GT.TBOIL(6).AND.TSEN.LT.TBOIL(8))GOTO500
      IF(TSEN.GE.TBOIL(8))GOTO224
      IF(TSEN.LE.TBOIL(6))GOTO228
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
      IF(ONF.GT.0.5)GOTO310
      IF(TSEN.GT.TBOIL(7))GOTO500
      ONF=1.
      WFUEL=TAB1(NP,TBOIL,FRGBL,TSEN)
      WAIR=TAB1(NP,TBOIL,AIRBL,TSEN)
      GOTO600
310   IF(TSEN.GE.TBOIL(8))GOTO315
      ONF=1.
      WFUEL=TAB1(NP,TBOIL,FRGBL.TSEN)
      WAIR=TAB1(NP,TBOIL,AIRBL,TSEN)
      GOTO300
315   ONF=0.
500   IF(ONF.GT.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:

$$\frac{dT_g}{dt} = \left(\frac{1}{C_p w}\right)_g [(C_p w)_g (T_1 - T_2) - Q_{gw}] \qquad (2)$$

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

For Boiler Furnace and Tube Walls:

$$\frac{dT_w}{dt} = \frac{1}{(C_p m)_w} (Q_{gw} - Q_{wf}) \qquad (3)$$

For Water or Steam

$$\frac{dT_f}{dt} = \frac{1}{(C_p m)_f} \{[w_f (h_1 - h_2)]_f + Q_{wf}\} \qquad (4)$$

For Boiler Shell

$$\frac{dT_s}{dt} = \frac{1}{(C_p m)_s} (Q_{ws} - Q_{sa}) \qquad (5)$$

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 α 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

$$Q_{gw} = (C_p w)_g (T_1 - T_2) \qquad (6)$$

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:

$$\frac{dT_f}{dt} = \frac{1}{[(C_p m)_w + (C_p m)_f]} \{[w(h_1 - h_2)] + Q_{gw}\} \qquad (7)$$

The wall temperature can then be calculated from the equation:

$$T_w = T_f + \frac{1}{(A\alpha)_{wf}} (Q_{gf}) \qquad (8)$$

where A and α 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:

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

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

A_R = refractory surface area

A_S = sink surface area

C_S = ratio of A_S to $(A_S \pm A_R)$

σ = Stefan-Boltzmann constant

α_c = convective heat transfer coefficient

ε_G = gas emissivity

ε_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

$K = T_S/T_{AG}$, ratio of the sink surface to the furnace gas temperature

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

$$\alpha_c = 0.023\frac{k}{D}(Re)^{0.8}(Pr)^{0.4} \qquad (10)$$

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,PCO2,PH2O,PSO2,PO2,PN2,RATF,RWTF,RPTF,
     %HFUEL,CPFUEL,TFUEL,BTUHK,EXAIR,TAIR,
     %FVOL,FSA,FRA,FDIAM,FSEM,TS,Q,TAF,TGE)
C
C  *** SIMULATE STIRRED REACTORS
C
      COMMON/WRITE/IWRITE
      HHV=HFUEL+CPFUEL*(TFUEL-TAIR)
      W=1000.*BTUHK/HFUEL
      HF=W*HHV
      ERR=0.001
      CP1=0.24
      CP=0.
      PTT=14.7*PTOTAL
      IF(IWRITE.LE.1)GOTO710
      WRITE(6,904)PTOTAL,PCO2,PH2O,PSO2,PO2,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
      TRA=TAIR+459.67
      TRF=TFUEL+459.67
      W=W*RPTF
      WH2O=18.*PH2O/(44.*PCO2+32.*PO2+64.*PSO2+28.*PN2)
      IF(IWRITE.LE.1)GOTO712
      WRITE(6,906)WH2O
712   CONTINUE
906   FORMAT(2X,'WH2O=',1PE11.3)
      SIGMA=0.1713E-08
      AC=0.78539816*FDIAM*FDIAM
      ALF=0.
      BLF=0.
      CLF=0.
      ATOTAL=FSA+FRA
      CS=FSA/ATOTAL
      AL=3.5*FVOL/ATOTAL
C
C  CALCULATE ADIABATIC FLAME TEMPERATURE
C
      TAF=TAFF(HHV,RWTF,RPTF,PCO2,PH2O,PO2,PSO2,
     8PN2,CP1,TRA,ERR,CP)
      IF(IWRITE.LE.1)GOTO700
      WRITE(6,900)TAF
900   FORMAT(2X,'TAF=',1PE11.3)
700   CONTINUE
C
C  CALCULATE RADIATIVE HEAT TRANSFER
C
      IF(IWRITE.LE.1)GOTO766
      WRITE(6,902)
766   CONTINUE
      TG2=TAF-500
      ITR=0
300   ITR=ITR+1
      TAG=0.5*(TAF+TG2)
      CPOE=CPF(TRA,TG2,PCO2,PH2O,PO2,PSO2,PN2)
      CPAE=CPF(TG2,TAF,PCO2,PH2O,PO2,PSO2,PN2)
      CPOA=CPF(TRA,TAF,PCO2,PH2O,PO2,PSO2,PN2)
      I=2
      TT=TAG-459.67
      CALL PRDPR(TT,PCO2,PH2O,PO2,PN2,PSO2,AMU,AKK)
```

FIGURE 4 LISTING OF SUBROUTINE SR

```
      PR=PRNB(AMU,CPAE,AKK)
      RE=RENB(W,AMU,AC,FDIAM)
      H=SGHT(RE,PR,AKK,FDIAM,ALF,BLF,CLF)
      GE=GEF(PCO2,PH2O,AL,TAG)
      AGS=GS(ATOTAL,CS,GE,FSEMD
      TRATIO=TRS/TAG
      AGS=AGS*(1.-TRATIO**3)/(1.-TRATIO**4)
      AGS=AGS+2.*FSA*H/(SIGMA*(TAG+TRS)**3)
      Q=AGS*SIGMA*(TAG**4-TRS**4)
      CPWOE=CPOE*W
      CPWOA=CPOA*W
      CCOAT=CPWOA*(TAF-TRA)*(HF-Q)
      CCOE=CPWOE*HF
      TGCAL=CCOAT/CCOE+TRA
      DTG2=TGCAL-TG2
      IF(IWRITE.LE.1)GOTO755
      WRITE(6,912)TAF,TG2,DTG2,Q,HF
755   CONTINUE
902   FORMAT(2X,'TAF',8X,'TG2',8X,'DTG2',7X,'Q',10X,'HF')
912   FORMAT(5(1PE11.3))
702   CONTINUE
      IF(ABS(DTG2).LE.10.)GOTO100
      IF(ITR.GT.1)GOTO200
      DTG1=DTG2
      TG1=TG2
      TG2=TG2+100.
      IF(DTG1.LT.0.)TG2=TG2-200.
      GOTO300
200   TG=TG1-DTG1*(TG2-TG1)/(DTG2-DTG1)
      IF(ABS(DTG1).LT.ABS(DTG2))GOTO250
      DTG1=DTG2
      TG1=TG2
250   TG2=TG
      GOTO300
100   TGE=TG2-459.67
      TAF=TAF-459.67
      RETURN
      END
```

FIGURE 4 <u>(CONTINUED)</u>

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:

$$\alpha_c = a(Re)^b(Pr)^c\left(\frac{k}{D}\right), \text{ for convective heat transfer coefficient} \tag{11}$$

$$\alpha_r = \frac{4\sigma T_{12}^3}{\frac{1}{\varepsilon_G}+\frac{1}{\varepsilon_S} - 1}, \text{ for radiative heat transfer coefficient} \tag{12}$$

$$\alpha = \alpha_c + \alpha_r, \text{ overall heat transfer coefficient} \tag{13}$$

$$Q_{gw} = (C_p w)_g (T_1 - T_w)\left[1 - \exp\left(-\frac{A\alpha}{C_p w}\right)_{gw}\right], \text{ for gas/tube interface heat flux} \tag{14}$$

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,PCO2,PH2O,PSO2,PN2,PO2,WGAS,
     *GSAS,GSVL,GSAC,GSCD,GSA,GSB,GSC,GSE,Q,TGE)
C
C *** LONG TUBE REACTORS
C
C   INPUT DATA:
C     TGI       GAS INLET TEMPERATURE                         F
C     TS        WALL SURFACE TEMPERATURE                      F
C     PTOTAL    TOTAL PRESSURE                                ATM
C     PCO2      MOLE FRACTION FOR CO2                         ---
C     PH2O      MOLE FRACTION FOR H2O                         ---
C     PSO2      MOLE FRACTION FOOR SO2                         ---
C     PN2       MOLE FRACTION FOR N2                          ---
C     PO2       MOLE FRACTION FOR O2                          ---
C     WGAS      GAS FLOW RATE                                 LB/HR
C     GSAS      SURFACE AREA                                  SQFT
C     GSVL      VOLUME                                        CUFT
C     GSAC      FLOW CROSS SECTIONAL AREA                     SQFT
C     GSCD      HEAT TRANSFER CHARACTERISTIC DIMENSION        FT
C     GSA       COEFFICIDNT IN NU EXPRESSION                  ---
C     GSB       COEFFICIENT IN NU EXPRESSION                  ---
C     GSC       COEFFICIENT IN NU EXPRESSION                  ---
C     GSE       TUBE SURFACE EMISSIVITY                       ---
C   OUTPUT DATA:
C     Q         HEAT TRANSFER RATE                            BTU/HR
C     TGE       GAS EXIT TEMPERATURE                          F
C
C *** CALCULATION BEGINS:
      TAV=0.5*(TGI+TGE)
      TTGI=TGI+459.67
      TTGE=TGE+459.67
      CPGAS=CPF(TTGI,TTGE,PCO2,PH2O,PO2,PSO2,PN2)
      CALL PRDPR(TAV,PCO2,PH2O,PO2,PN2,PSO2,AMM,AKK)
      PR=PRNB(AMM,CPGAS,AKK)
      RE=RENB(WGAS,AMM,GSAC,GSCD)
      HC=SGHT(RE,PR,AKK,GSCD,GSA,GSB,GSC)
      TGS=0.5*(TAV**4+TS**4)
      TGS=TGS**0.25
      XL=0.35*GSVL/GSAS
      PPCO2=PCO2*PTOTAL
      PPH2O=PH2O*PTOTAL
      EMGS=GEF(PPCO2,PPH2O,XL,TGS)
      SIGMA=0.1713E-08
      HALL=1./GSE+1./EMGS-1.
      HALL=4.*SIGMA*TAV**3/HALL
      HALL=HC+HALL
      CPW=CPGAS*WGAS
      ANTU=GSAS*HALL/CPW
      QQ=(TGI-TS)*(1.-EXP(-ANTU))
      TGE=TGI-QQ
      Q=CPW*QQ
      RETURN
      END
```

FIGURE 5 <u>LISTING OF SUBROUTINE LT</u>

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]:

$$\alpha = a\ (Re)^b (Pr)^c \left(\frac{k}{D}\right) \qquad (15)$$

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

$$Q_{gw} = (C_p w)_g (T_1 - T_w)\left[1 - \exp\left(-\frac{A\alpha}{C_p w}\right)_g\right] \qquad (16)$$

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(QGT,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     PNOW=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
      RH=0.
      CALL AIRPR(I,TAIR,PAIR,RH,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)
      CPW=CP*WAIR
      ANTU=ALPHA*AS/CPW
      DELT=(TAIR-TTB)*(1.-EXP(-ANTU))
      TGS=TAIR-DELT
      QGT=CPW*DELT
      RETURN
      END
```

FIGURE 6 LISTING OF SUBROUTINE FG

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:

$$\alpha = 76.92(Re)_B^{0.067} Pr^{0.7} \left(\frac{k}{D_B} \right) \tag{17}$$

$$\alpha = 0.023(Re)^{0.8}(Pr)^{0.4} \left(\frac{k}{D} \right) \tag{18}$$

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:

$$D_b = \frac{\gamma}{g(\rho_\ell - \rho_v)} \tag{19}$$

where γ = water surface tension coefficient

g = gravitational acceleration

ρ_ℓ = water density

ρ_v = 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:

$$Q_{sa} = UA(T_f - T_a) \qquad (20)$$

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:

$$U = 1/(1/\alpha_{fs} + 1/\alpha_s + 1/\alpha_{sa}) \qquad (21)$$

```
      FUNCTION DB(ROL,ROV,SIGMA)
C
C  *** CALCULATE NUCLEATION BUBBLE DIAMETER
C
C   INPUT DATA:
C
C      ROL        LIQUID DENSITY                          LB/CUFT
C      ROV        VAPOR DENSITY                           LB/CUFT
C      SIGMA      SURFACE TENSION                         LB/FT
C
C   OUTPUT DATA:
C
C      DB         DIAMETER OF BOILING NUCLEATION BUBBLES  FT
C
      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
C  *** CALCULATE SINGLE-PHASE HET TRANSFER COEFFICIENT
C
      COMMON/WRITE/IWRITE
      IF(IWRITE.LE.1)GOTO704
      WRITE(6,706)RE,PR,AK,D,ALF,BLF,CLF
  704 CONTINUE
  706 FORMAT(/2X,5HSGHT:/2X,2HRE,9X,2HPR,9X,2HAK,9X,1HD/
     %4(1PE11.3)/2X,3HALF,8X,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=0.023
      TBLF=0.8
      TCLF=0.4
   10 SGHT=TALF*AK*RE**TBLF*PR**TCLF/D
      IF(IWRITE.LE.1)GOTO700
      WRITE(6,702)SGHT
  700 RETURN
  702 FORMAT(/2X,5HSGHT=,1PE11.3)
      END
```

FIGURE 8 LISTING OF SUBROUTINE SGHT

In this equation, α_{fs} is calculated by McAdams' equation:

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

α_s is calculated by the wall conductance equation:

$$\alpha_s = \frac{k}{x} \tag{23}$$

and α_{sa} is calculated by the free convective equation

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

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 SH for calculating the heat loss at the boiler shell. A detailed listing of subroutine 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
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 FOE 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 μ & 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

4. COMMERCIAL BOILER TRANSIENT ANALYSIS COMPUTER PROGRAM DEPAB2

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.

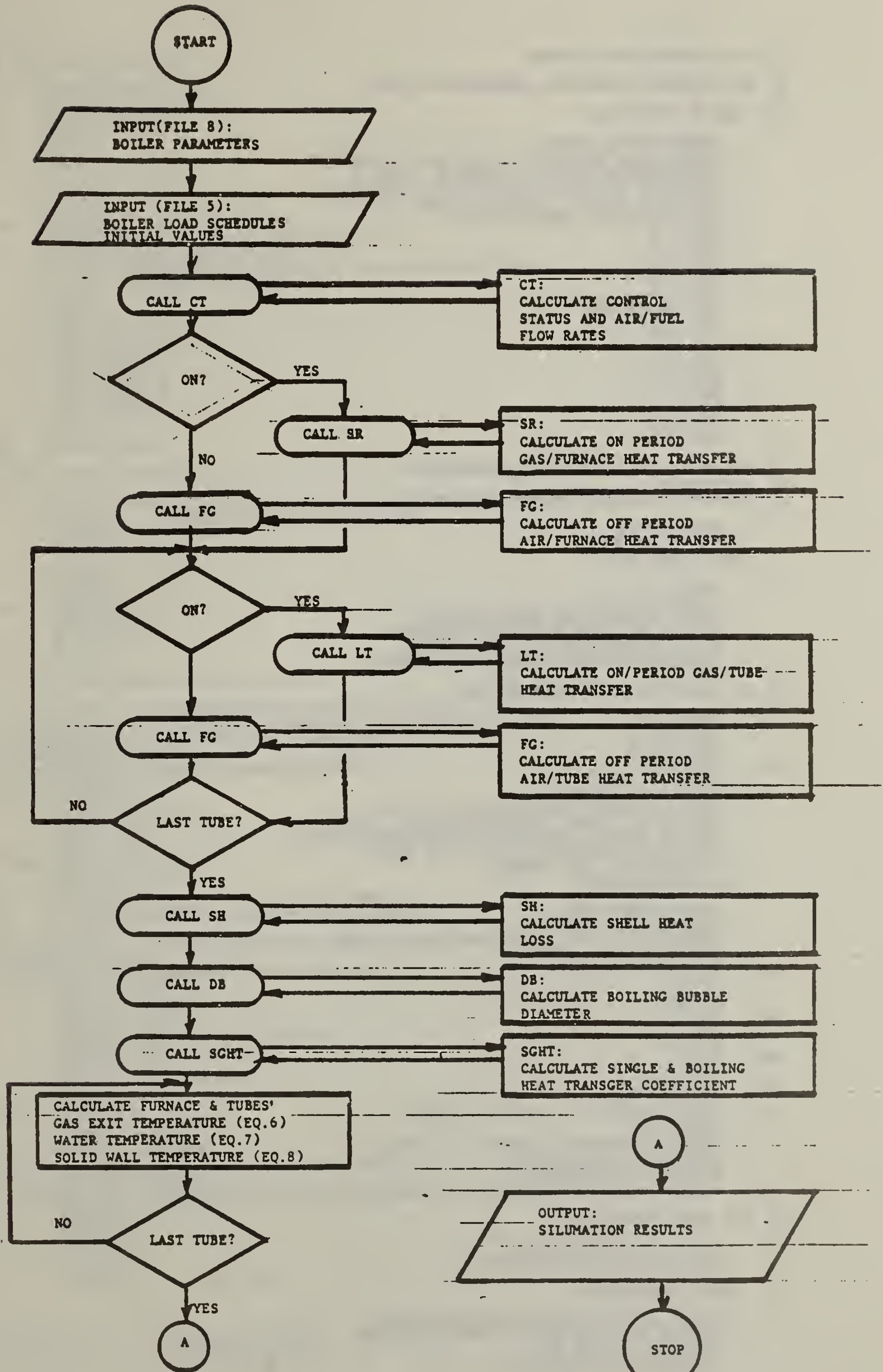


FIGURE 11 FLOWCHART FOR DEPAB2

```
C
C  *** PROGRAM NAME: DEPAB2
C
C  *** PURPOSE: SIMULATE LARGE-SCALE BOILERS
C
C   DEFINE INPUT FILE
C
      COMMON/WRITE/IWRITE
      COMMON/BTLD/TMIN(60),TIA(60),TOA(60),HDMD(60)
      COMMON/CONTRL/TBOIL(8),FRCBL(8),AIRBL(8)
      DIMENSION TGS(51),TTB(51),TWT(51),QCT(51)
      DIMENSION TAS(50),TVL(50),TAC(50),TDI(50),
     *TBA(50),TBB(50),TBC(50),TBE(50)
      DO5I=1,51
      TGS(I)=0.
      TTB(I)=0.
      TWT(I)=0.
      QCT(I)=0.
      IF(I.EQ.51)GOTO5
      TAS(I)=0.
      TVL(I)=0.
      TAC(I)=0.
      TDI(I)=0.
      TBA(I)=0.
      TBB(I)=0.
      TBC(I)=0.
      TBE(I)=0.
5     CONTINUE
C
C ***************************************************
C  INPUT DATA                                       *
C ***************************************************
C
      WRITE(6,996)
      READ(5,*) IWRITE
C   INPUT FUEL DATA:
C
      PTOTAL=1.
      PAIR=PTOTAL*14.7
      READ(8,*) CARB,HYDR,OXYG,XNTR,SULF
      WRITE(6,901) CARB,HYDR,OXYG,XNTR,SULF
      READ(8,*) HFUEL,CPFUEL,TFUEL,BTUHK
      WRITE(6,903) HFUEL,CPFUEL,TFUEL,BTUHK
C
C *** INPUT CONTROL SUBSYSTEM DATA
C
      DO30I=1,8
      TBOIL(I)=0.
      FRCBL(I)=0.
30    AIRBL(I)=0.
      READ(8,*) ICTYPE
      WRITE(6,916) ICTYPE
      READ(8,*) TASEN,TAAIR,FRCFL,EXAFL,AIROF
      WRITE(6,918) TASEN,TAAIR,FRCFL,EXAFL,AIROF
      CALL PP(PTOTAL,CARB,HYDR,OXYG,XNTR,SULF,EXAFL,
     *PCO2,PH2O,PSO2,PO2,PN2,RATF,RPTF,RWTF)
      FRLTNT=RWTF*(1050./HFUEL)
      AIRFL=RATF*FRCFL

      AIROF=AIROF*AIRFL
      THAIR=RATF/(1.+EXAFL)
      WRITE(6,805) TASEN,TAAIR,FRCFL,AIRFL,   OF
      GOTO(21,22,23),ICTYPE
21    I1=6
      I2=7
      GOTO29
22    I1=6
      I2=8
      GOTO29
23    I1=1
      I2=8
29    WRITE(6,917)
      DO31I=I1,I2
31    READ(8,*)TBOIL(I),FRCBL(I),AIRBL(I)
      DO32I=1,8
      WRITE(6,803) TBOIL(I),FRCBL(I),AIRBL(I)
      FRCBL(I)=FRCFL*FRCBL(I)
      AIRBL(I)=AIRFL*AIRBL(I)
32    WRITE(6,803) TBOIL(I),FRCBL(I),AIRBL(I)
C
C  *** INPUT WATER DATA
C
      READ(8,*) WTOST,TIN,TOUT
      WRITE(6,909) WTOST,TIN,TOUT
C
C   INPUT FURNACE DATA
C
      READ(8,*) FVOL,FSA,FCA,FRA,FDIAM,FSEM
      WRITE(6,994) FVOL,FSA,FCA,FRA,FDIAM,FSEM
      READ(8,*) FNA,FNB,FNC
      WRITE(6,923) FNA,FNB,FNC
```

FIGURE 12 LISTING OF DEPAB2 MAIN PROGRAM

```
C
C *** INPUT TUBE DATA
C
      READ(8,*)NT1,NT2
      WRITE(6,925)NT1,NT2
      WRITE(6,924)
      K=1
      L=NT1
      DO40J=1,2
      IF(J.EQ.1)GOTO44
      K=NT1+1
      L=NT2
44    CONTINUE
      READ(8,*)TAS(K),TVL(K),TAC(K),TDI(K),
     *TBA(K),TBB(K),TBC(K),TBE(K)
      WRITE(6,806)TAS(K),TVL(K),TAC(K),TDI(K),TBA(K),TBB(K)
      WRITE(6,802)TBC(K),TBE(K)
      M=K+1
      DO40I=M,L
      TAS(I)=TAS(K)
      TVL(I)=TVL(K)
      TAC(I)=TAC(K)
      TDI(I)=TDI(K)
      TBA(I)=TBA(K)
      TBB(I)=TBB(K)
      TBC(I)=TBC(K)

40    TBE(I)=TBE(K)
C
C *** INPUT WATER DATA
C
      READ(8,*)STMVL,WTAC,WTCD,WTA,WTB,WTC
      WRITE(6,911)STMVL,WTAC,WTCD,WTA,WTB,WTC
      STMCAP=0.9*STMVL
      WTAS=FSA
      I=NT2
      DO50K=1,I
      WTAS=WTAS+TAS(K)
50    CONTINUE
      BLGA=76.92
      BLGB=0.667
      BLGC=-0.7
C
C  *** INPUT SHELL AND WEIGHT DATA
C
      READ(8,*)SHARE,SHUFT,SHHGT,SHCAP,FNCAP,TBCAP,WTCAP
      WRITE(6,912)SHARE,SHUFT,SHHGT,SHCAP,FNCAP,TBCAP,WTCAP
C ****************************************
C LOAD SCHEDULING                        *
C ****************************************
100   CONTINUE
      WRITE(6,915)
      READ(5,*)NTIME
      DO10I=1,60
      TMIN(I)=0.
10    HDMD(I)=0.
      DO11I=1,NTIME
      WRITE(6,934)
      READ(5,*)TMIN(I),TIA(I),TOA(I),HDMD(I)
11    WRITE(6,804)TMIN(I),TIA(I),TOA(I),HDMD(I)
C
C ****************************************
C INITIAL VALUES                         *
C ****************************************
      WRITE(6,935)
      READ(5,*) ICYCLE
      WRITE(6,1000)
      READ(5,*)TIME,DT,IPRNT,ICALC
      TSTART=TIME
      WRITE(6,1002)
      READ(5,*)ONF,TSEN,TBL
      DO203I=1,31
203   TTB(I)=TBL
      DMT=0.01666667*DT
      WRITE(6,1003)
      READ(5,*)TSH,TRW
C ****************************************
C  CALCULATION BEGINS                    *
C ****************************************
      NCYCLE=1
      TIMCYC=0.
      QUDCYC=0.
      QIPCYC=0.
      QIPNOW=0.
      ETANOW=0.
```

FIGURE 12 (CONTINUED)

```
      QUDNOW=0.
      QIPTOT=0.
      QUDTOT=0.
      ETATOT=0.
      QFWAT=0.
      QSUPLD=0.
      QLOAD=0.
      QSHELL=0.
      QEXHT=0.
      QLTNT=0.
      ISTART=0
      NPRNT=0
      NCALC=0
      WRITE(6,932)
310   IF(ISTART.EQ.0.AND.TIME.LT.0)GOTO300
      NPRNT=0
      NCALC=0
      IF(TSTART.LT.0.0001)TIME=0.
      ISTART=1
      CNDCYC=ONF
      WRITE(6,932)
      WRITE(6,933)TIME,QSUPLD,QLOAD,QFWAT,QSHELL,QEXHT,QLTNT,
     *TGS(1),TGS(NT2+1),TTB(1),TTB(NT2+1),TBL,TSEN,
     *QIPNOW,QUDNOW,ETANOW,QIPTOT,QUDTOT,ETATOT
300   TIME=TIME+DT
      NCALC=NCALC+1
      NPRNT=NPRNT+1
C
C *** HEAT DEMAND
C
      TIDA=TAB1(NTIME,TMIN,TIA,TIME)
      TODA=TAB1(NTIME,TMIN,TOA,TIME)
      QLOAD=TAB1(NTIME,TMIN,HDMD,TIME)
      IF(IWRITE.GE.1)WRITE(6,1001)TIME,TIDA,TODA,QLOAD
C
C *** WATER & STEAM PROPERTIES
C
      CALL H2OLQ(TBL,WATRO,WATCP,WATAK,WATAM,
     *WATST,WATBT)
      CALL H2OVP(TBL,STMRO,STMCP,STMAK,STMAM,
     *STMHFG,STMBT)
      QWAT=0.25*HFUEL*FRCFL
      IF(QWAT.LT.QLOAD)QWAT=QLOAD
      WMAS=QWAT/STMHFG
      BBDIA=DB(WATRO,STMRO,WATST)
      PR=PRNB(WATAM,WATCP,WATAK)
      REB=RENB(WMAS,WATAM,WTAS,BBDIA)
      REC=RENB(WMAS,WATAM,WTAC,WTCD)
      BLALF=SGHT(REB,PR,WATAK,BBDIA,BLGA,BLGB,BLGC)
      CVALF=SGHT(REC,PR,WATAK,WTCD,WTA,WTB,WTC)
      IF(IWRITE.GE.1)WRITE(6,928)BLALF,CVALF
C
C *** BOILER CONTROL STATUS
C
      CALL CT(ONF,WFUEL,WAIR,WGAS,TSEN,
     *TBL,ICTYPE,TASEN,TAAIR,AIROF,DT)
      IF(IWRITE.GE.1)WRITE(6,919)ONF,WFUEL,WAIR,WGAS,TSEN,TBL
C
C *** GAS/FURNACE HEAT TRANSFER
C
      CALL BG(BTUHK,EXAIR,HFUEL,CPFUEL,
     *TFUEL,THAIR,WFUEL,WAIR)
      IF(IWRITE.GE.1)WRITE(6,921)BTUHK,EXAIR
      IF(WFUEL.GT.0.0001)GOTO201
      CALL FG(QGT(1),TGS(1),TTB(1),WAIR,
     *PAIR,TIDA,FCA,FSA,FDIAM,FNA,FNB,FNC)
      IF(IWRITE.GE.1)WRITE(6,922)
      IF(IWRITE.GE.1)WRITE(6,803)QGT(1),TGS(1),TIDA
      GOTO202
201   CALL SR(PTOTAL,PCO2,PH2O,PSO2,PO2,PN2,RATF,RWTF,
     *RPTF,HFUEL,CPFUEL,TFUEL,BTUHK,EXAIR,TIDA,FVOL,FSA,FRA,
     *FDIAM,FSEM,TTB(1),QGT(1),TGSI,TGS(1))
      IF(IWRITE.GE.1)WRITE(6,922)
      IF(IWRITE.GE.1)WRITE(6,803)QGT(1),TGS(1),TGSI
202   CONTINUE
C
C *** GAS/TUBE HEAT TRANSFER
C
      DO210I=1,NT2
      J=I+1
      IF(WFUEL.GT.0.0001)GOTO205
      CALL FC(QGT(J),TGS(J),TTB(J),WAIR,PAIR,TGS(I),
     *TAC(I),TAS(I),TDI(I),TBA(I),TBB(I),TBC(I))
      IF(IWRITE.GE.1)WRITE(6,920)QGT(J),TGS(J)
      GOTO210
205   CALL LT(TGS(I),TTB(J),PTOTAL,PCO2,PH2O,PSO2,PN2,PO2,
     *WGAS,TAS(I),TVL(I),TAC(I),TDI(I),TBA(I),TBB(I),TBC(I),
     *TBE(I),QGT(J),TGS(J))
      IF(IWRITE.GE.1)WRITE(6,803)QGT(J),TGS(J),TGS(I)
210   CONTINUE
```

FIGURE 12 (CONTINUED)

```
C
C
C *** SHELL HEAT TRANSFER.
C
      CALL SH(QSHELL,TSH,TBL,TIDA,CVALF,
     *SHARE,SHUFT,SHHGT)
      IF(IWRITE.GE.1)WRITE(6,926)TSH,QSHELL
C
C *** HEAT BALANCE
C
      QSUPLD=1000.*BTUHK
      TALF=CVALF+BLALF
      TBL1=TBL
      STMVOL=1./(STMVL*STMHFG)
      FWCPR=WATCP*QLOAD*(1./STMHFG)
      J=NT2+1
      QTOTAL=0.
      DO220I=1,J
220   QTOTAL=QTOTAL+QGT(I)
      CTOTAL=SHCAP+FNCAP+TBCAP+WTCAP+STMCAP
      IF(IWRITE.GE.1)WRITE(6,929)
      IF(IWRITE.GE.1)WRITE(6,803)TBL,PBL
      QGROSS=QTOTAL-QSHELL
      QFWAT=FWCPR*(TBL-TRW)
      QNET=QGROSS-QFWAT
      QSTEAM=DDT*(QNET-QLOAD)
      DTBL=QSTEAM*(1./CTOTAL)
      TBL=TBL+DTBL
      PBL=STSATP(TBL)
      IF(IWRITE.GE.1)WRITE(6,803)TBL,PBL
      UA=FSA*TALF
      UC=FSA*CVALF
      TTB(1)=TBL+QGT(1)*(0.9/UA+0.1/UC)
      J=NT2+1
      DO270I=2,J
      UA=TAS(I-1)*TALF
      UC=TAS(I-1)*CVALF
      TTB(I)=TBL+QGT(I)*(0.9/UA+0.1/UC)
270   CONTINUE
      IF(IWRITE.GE.1)WRITE(6,930)
      IF(IWRITE.GE.1)WRITE(6,931)TTB
      QLTNT=FRLTNT*QSUPLD
      QEXHT=QSUPLD-QTOTAL-QLTNT
      QUDNOW=QFWAT+QLOAD
      IF(TIDA.GT.TODA)QUDNOW=QUDNOW-0.24*WAIR*(TIDA-TODA)
      QIPNOW=QSUPLD
      ETANOW=0.
      IF(QSUPLD.LE.0.0001)GOTO345
      ETANOW=QUDNOW*(1./QIPNOW)
345   CONTINUE
      IF(ISTART.LE.0)GOTO360
      IF(ICYCLE.EQ.0)GOTO400
      IF(NCYCLE.EQ.1.AND.ABS(ONF-CNDCYC).LE.0.0001)GOTO400
      IF(NCYCLE.NE.1)GOTO410
      CNDCYC=ONF
      NCYCLE=2
410   QIPCYC=QIPCYC+QIPNOW*DDT
      QUDCYC=QUDCYC+QUDNOW*DDT
      TIMCYC=TIMCYC+DT
      IF(NCYCLE.EQ.1)GOTO400
      IF(NCYCLE.EQ.2.AND.ABS(ONF-CNDCYC).LE.0.0001)GOTO430
      IF(NCYCLE.EQ.3)GOTO430
      NCYCLE=3
      CNDCYC=ONF
430   IF(NCYCLE.EQ.3.AND.ABS(ONF-CNDCYC).GE.0.0001)GOTO450
      GOTO400
450   ETACYC=QUDCYC*(1./QIPCYC)
      WRITE(6,936)TIMCYC,QUDCYC,QIPCYC,ETACYC
      NCALC=ICALC
400   CONTINUE
      QIPTOT=QIPTOT+QIPNOW*DDT
      QUDTOT=QUDTOT+QUDNOW*DDT
      IF(QIPTOT.LE.1.E-30)GOTO355
      ETATOT=QUDTOT*(1./QIPTOT)
      GOTO360
355   ETATOT=0.
360   CONTINUE
      IF(NPRNT.LT.IPRNT)GOTO320
      NPRNT=0
      WRITE(6,933)TIME,QSUPLD,QLOAD,QFWAT,QSHELL,QEXHT,QLTNT,
     *TGS(1),TGS(NT2+1),TTB(1),TTB(NT2+1),TBL,TSEN,
     *QIPNOW,QUDNOW,ETANOW,QIPTOT,QUDTOT,ETATOT
320   IF(ISTART.EQ.0)GOTO310
      IF(NCALC.LT.ICALC)GOTO300
```

FIGURE 12 (CONTINUED)

```
      WRITE(6,908)
      READ(5,*) ICONT
      IF(ICONT.GT.0)GOTO100
  801 FORMAT(1(1PE11.3))
  802 FORMAT(2(1PE11.3))
  803 FORMAT(3(1PE11.3))
  804 FORMAT(4(1PE11.3))
  805 FORMAT(5(1PE11.3))
  806 FORMAT(6(1PE11.3))
  807 FORMAT(7(1PE11.3))
  808 FORMAT(8(1PE11.3))
  811 FORMAT(I10)
  901 FORMAT(2X,'CARB',7X,'HYDR',7X,'OXYG',7X,
     %'XNTR',7X,'SULF'/5(1PE11.3))
  902 FORMAT(2X,'HFUEL',6X,'CPFUEL',5X,'TFUEL',6X,'KBTUH'/
     %4(1PE11.3))
  903 FORMAT(2X,'EXAIR',6X,'TAIR'/2(1PE11.3))
  904 FORMAT(2X,'FVOL',7X,'FSA',8X,'FCA',8X,'FRA',8X,'FDIAM',
     %6X,'FSEM'/6(1PE11.3))
  906 FORMAT(2X,'IWRITE=?')
  907 FORMAT(2X,'BTUHK,EXAIR,TAIR,TEX,TOA=?')
  908 FORMAT(2X,'ICONTINUE=?')
  909 FORMAT(2X,5HWTUST,6X,3HTIN,8X,4HTOUT/3(1PE11.3))
  910 FORMAT(2X,4HGSAS,7X,4HGSVL,7X,4HGSAC,7X,4HGSCD,7X,3HGSA,7X,3HGSB/
     %6(1PE11.3)/2X,3HGSC,8X,3HGSE/2(1PE11.3))
  911 FORMAT(2X,5HSTMVL,6X,4HWTAC,7X,4HWTCD,7X,3HWTA,7X,3HWTB,
     &8X,3HWTC/6(1PE11.3))
  912 FORMAT(2X,5HSHARE,6X,5HSHUFT,6X,5HSHHGT,6X,5HSHCAP/
     %4(1PE11.3)/2X,5HFNCAP,6X,5HTBCAP,6X,5HWTCAP/
     %3(1PE11.3))
  913 FORMAT(/2X,19HDTIME,TTIME,PRINT=?)
  914 FORMAT(/2X,4HTIME,7X,1HQ,10X,3HETA,8X,4HTGSI/4(1PE11.3)/2X,
     %4HTGS:/6(1PE11.3)/5(1PE11.3)/2X,
     %4HTTB:/6(1PE11.3)/5(1PE11.3)/2X,
     %4HQGT:/6(1PE11.3)/5(1PE11.3))
915    FORMAT(2X,'NTIME=?')
916    FORMAT(2X,'ICTYPE=',I3)
917    FORMAT(2X,'TBOIL',6X,'FRGBL',6X,'AIRBL')
918    FORMAT(2X,'TASEN',6X,'TAAIR',6X,'FRGFL',6X,
      &'EXAFL',6X,'AIROF'/5(1PE11.3))
919    FORMAT(2X,'ONF',8X,'WFUEL',6X,'WAIR',7X,'WGAS',7X,
      %'TSEN',7X,'TBL'/6(1PE11.3))
920    FORMAT(2X,'QGT(1)',5X,'TGS(1)'/2(1PE11.3))
921    FORMAT(2X,'KBTUH',6X,'EXAIR'/2(1PE11.3))
922    FORMAT(2X,'QGT',8X,'TGS(OUT)',3X,'TGS(IN)')
923    FORMAT(2X,'FNA',8X,'FNB',8X,'FNC'/3(1PE11.3))
924    FORMAT(2X,'TAS',8X,'TVL',8X,'TAC',8X,'TDI',8X,
      %'TBA',8X,'TBB'/2X,'TBC',8X,'TBE')
925    FORMAT(2X,'NT1=',I5/2X,'NT2=',I5)
926    FORMAT(2X,'TSH',8X,'QSHELL'/2(1PE11.3))
928    FORMAT(2X,'BLALF',6X,'CVALF'/2(1PE11.3))
929    FORMAT(2X,'TBL',8X,'PBL')
930    FORMAT(2X,'BOILER TUBE TEMPERATURES:')
931    FORMAT(2X,8(6(1PE11.3)/)/3(1PE11.3))
932    FORMAT(////2X,'TIME:'/2X,'QSUPLD',5X,'QLOAD',6X,'QFWAT',6X,
      %'QSHELL',5X,'QEXHT',6X,'QLTNT'/
      %2X,'TGASFN',5X,'TGASTB',5X,'TTUBFN',5X,'TTUBTB',5X,
      %'TWATER',5X,'TSENSE'/
      %2X,'QIPNOW',5X,'QUDNOW',5X,'ETANOW',5X,
      %'QIPTOT',5X,'QUDTOT',5X,'ETATOT')
933    FORMAT(/1PE11.3/6(1PE11.3)/6(1PE11.3)/6(1PE11.3))
934    FORMAT(2X,'TMIN,TIA,TOA,HDMD=?')
935    FORMAT(2X,'ICYCLE=?')
936    FORMAT(//2X,'TIMCYC',5X,'QUDCYC',5X,
      %'QIPCYC',5X,'ETACYC'/4(1PE11.3))
1000   FORMAT(2X,'TIME,DT,IPRNT,ICALC=?')
1001   FORMAT(2X,'TIME',7X,'TIDA',7X,'TODO',7X,'QLOAD'/
      %4(1PE11.3))
1002   FORMAT(2X,'ONF,TSEN,TBL=?')
1003   FORMAT(2X,'TSH,TRW=?')
       CALL EXIT
       END
```

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.

5.2 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.,2.672,0.33,0.6,0.33
290 380.,54.,8.,1710.,337.,1500.,7500.
END OF FILE
->
```

FIGURE 13 A SAMPLE FILE 8 INPUT DATA FOR BOILER PARAMETERS

```
IWRITE=?
>0                                                                    TERMINAL INPUT
CARB        HYDR        OXYG        XNTR        SULF                  ECHOES OF FILE 8
2.070-001   7.900-001   2.300-003   1.600-003    .000                 DATA START
HFUEL       CPFUEL      TFUEL       KBTUH
2.340+004   5.200-001   6.500+001   1.675+004
ICTYPE=  3
TASEN       TAAIR       FRGFL       EXAFL       AIROF
2.000+000   2.000+000   7.160+002   2.500-001   3.000-001
2.000+000   2.000+000   7.160+002   1.487+004   4.460+003
TBOIL       FRGBL       AIRBL
2.200+002   1.000+000   1.000+000
2.200+002   7.160+002   1.487+004
2.240+002   9.000-001   9.000-001
2.240+002   6.444+002   1.338+004
2.280+002   8.000-001   8.000-001
2.280+002   5.728+002   1.189+004
2.320+002   7.000-001   7.000-001
2.320+002   5.012+002   1.041+004
2.360+002   6.000-001   6.000-001
2.360+002   4.296+002   8.921+003
2.400+002   5.000-001   5.000-001
2.400+002   3.580+002   7.434+003
2.440+002   4.000-001   4.000-001
2.440+002   2.864+002   5.947+003
2.500+002   4.000-001   4.000-001
2.500+002   2.864+002   5.947+003
WTOST       TIN         TOUT
2.000+000   2.000+002   2.120+002
FVOL        FSA         FCA         FRA         FDIAM       FSEM
2.640+002   1.450+002   1.060+001   2.100+001   3.670+000   8.000-001
FNA         FNB         FNC
2.300-002   8.000-001   4.000-001
NT1=     5
NT2=    10
TAS         TVL         TAC         TDI         TBA         TBB
TBC         TBE
5.000+001   1.900+001   5.000-001   2.100-001   2.300-002   8.000-001
4.000-001   8.000-001
5.000+001   1.900+001   5.000-001   2.100-001   2.300-002   8.000-001
4.000-001   8.000-001
STMVL       WTAC        WTCD        WTA         WTB         WTC
2.500+002   1.800+001   2.672+000   3.300-001   6.000-001   3.300-001
SHARE       SHUFT       SHHGT       SHCAP
3.800+002   5.400+001   8.000+000   1.710+003
FNCAP       TBCAP       WTCAP
                                                                      FILE 8 DATA END
3.370+002   1.500+003   7.500+003
```

FIGURE 14 OUTPUT DATA FROM A SAMPLE DEPAB2 RUN

ADDITIONAL TERMINAL DATA ENTRIES

```
 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.
  .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:

```
TIME:
QSUPLD      QLOAD       QFWAT       QSHELL      QEXHT       QLTNT
TGASFN      TGASTB      TTUBFN      TTUBTB      TWATER      TSENSE
QIPNOW      QUDNOW      ETANOW      QIPTOT      QUDTOT      ETATOT

-2.000+001
 8.187+006   4.170+006   2.706+005   5.555+004   4.646+005   7.837+005
 2.270+003   4.303+002   7.736+002   3.012+002   2.420+002   2.404+002
 8.187+006   4.397+006   5.370-001    .000        .000        .000

-1.000+001
 8.060+006   4.170+006   2.792+005   5.630+004   4.534+005   7.715+005
 2.261+003   4.324+002   7.711+002   3.021+002   2.437+002   2.408+002
 8.060+006   4.406+006   5.467-001    .000        .000        .000

  .000
 7.752+006   4.170+006   2.877+005   5.704+004   4.163+005   7.420+005
 2.238+003   4.277+002   7.643+002   2.996+002   2.452+002   2.415+002
 7.752+006   4.416+006   5.697-001    .000        .000        .000


TIME:
QSUPLD      QLOAD       QFWAT       QSHELL      QEXHT       QLTNT
TGASFN      TGASTB      TTUBFN      TTUBTB      TWATER      TSENSE
QIPNOW      QUDNOW      ETANOW      QIPTOT      QUDTOT      ETATOT

  .000
 7.752+006   4.170+006   2.877+005   5.704+004   4.163+005   7.420+005
 2.238+003   4.277+002   7.643+002   2.996+002   2.452+002   2.415+002
 7.752+006   4.416+006   5.697-001    .000        .000        .000

 1.000+001
 7.365+006   4.170+006   2.952+005   5.771+004   3.655+005   7.049+005
 2.206+003   4.186+002   7.553+002   2.958+002   2.465+002   2.424+002
 7.365+006   4.426+006   6.010-001   9.100+005   7.380+005   8.109-001

 2.000+001
 6.937+006   4.170+006   3.017+005   5.828+004   3.297+005   6.639+005
 2.162+003   4.072+002   7.432+002   2.914+002   2.475+002   2.434+002
 6.937+006   4.435+006   6.393-001   1.817+006   1.476+006   8.126-001

 3.000+001
 6.700+006   4.170+006   3.068+005   5.875+004   2.967+005   6.413+005
 2.138+003   3.966+002   7.375+002   2.886+002   2.485+002   2.445+002
 6.700+006   4.441+006   6.629-001   2.721+006   2.214+006   8.137-001
 ICONTINUE=?
>0
```

FIGURE 14 <u>(CONTINUED)</u>

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.

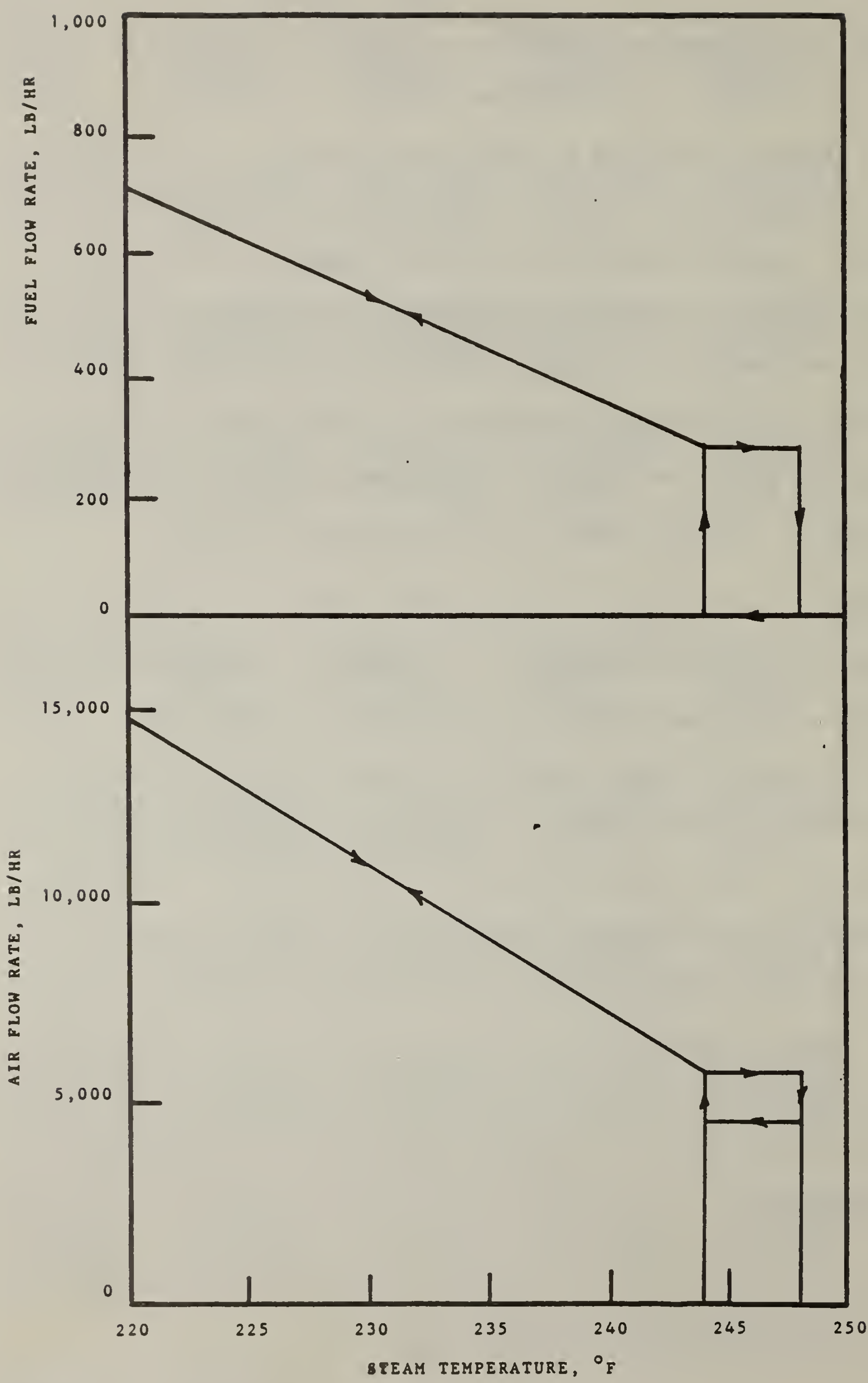


Figure 15 CONTROL LOGIC FOR A BOILER UNDER INVESTIGATION

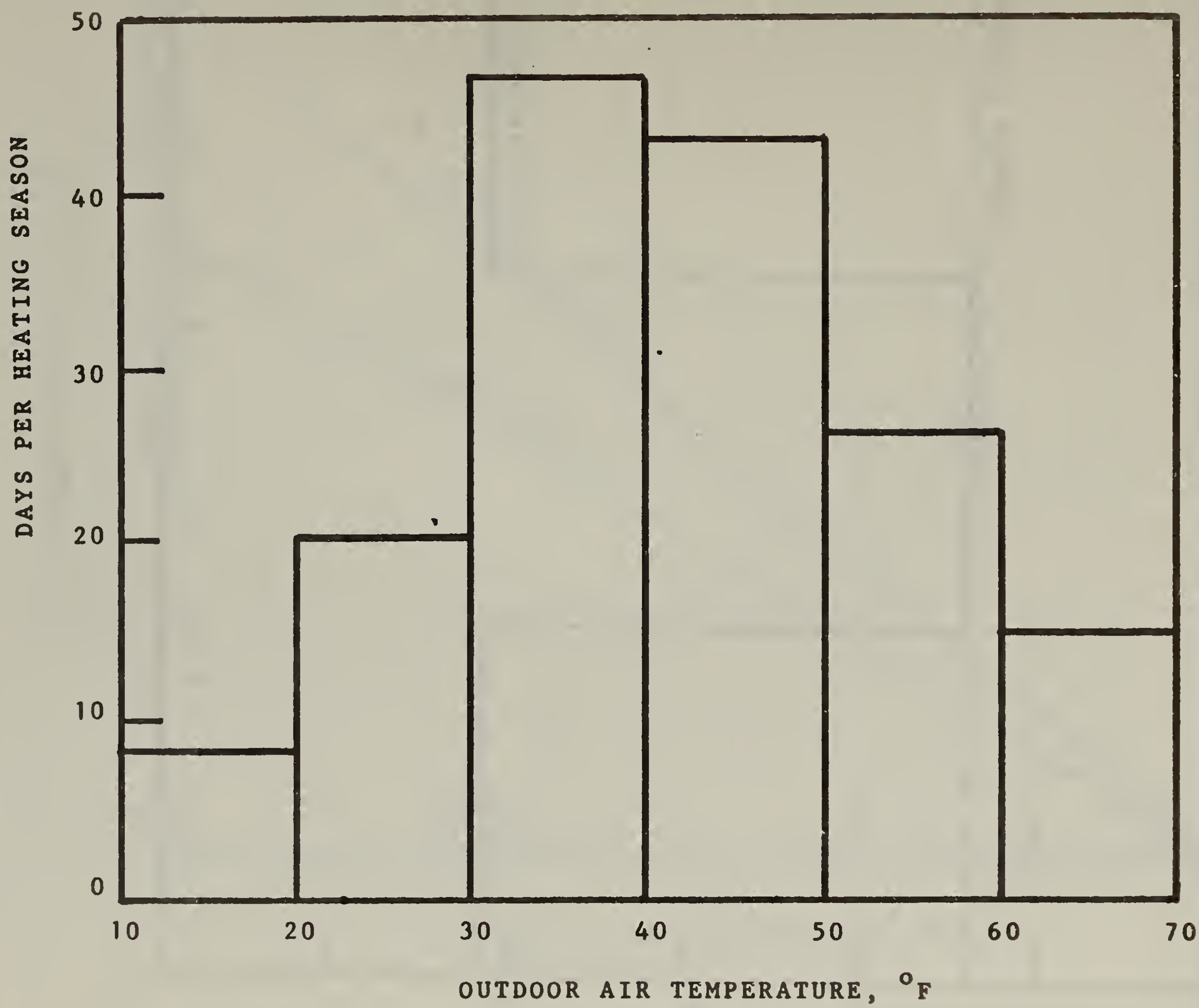


FIGURE 16 <u>TYPICAL WEATHER AT WASHINGTON D.C. DURING THE HEATING SEASON</u>

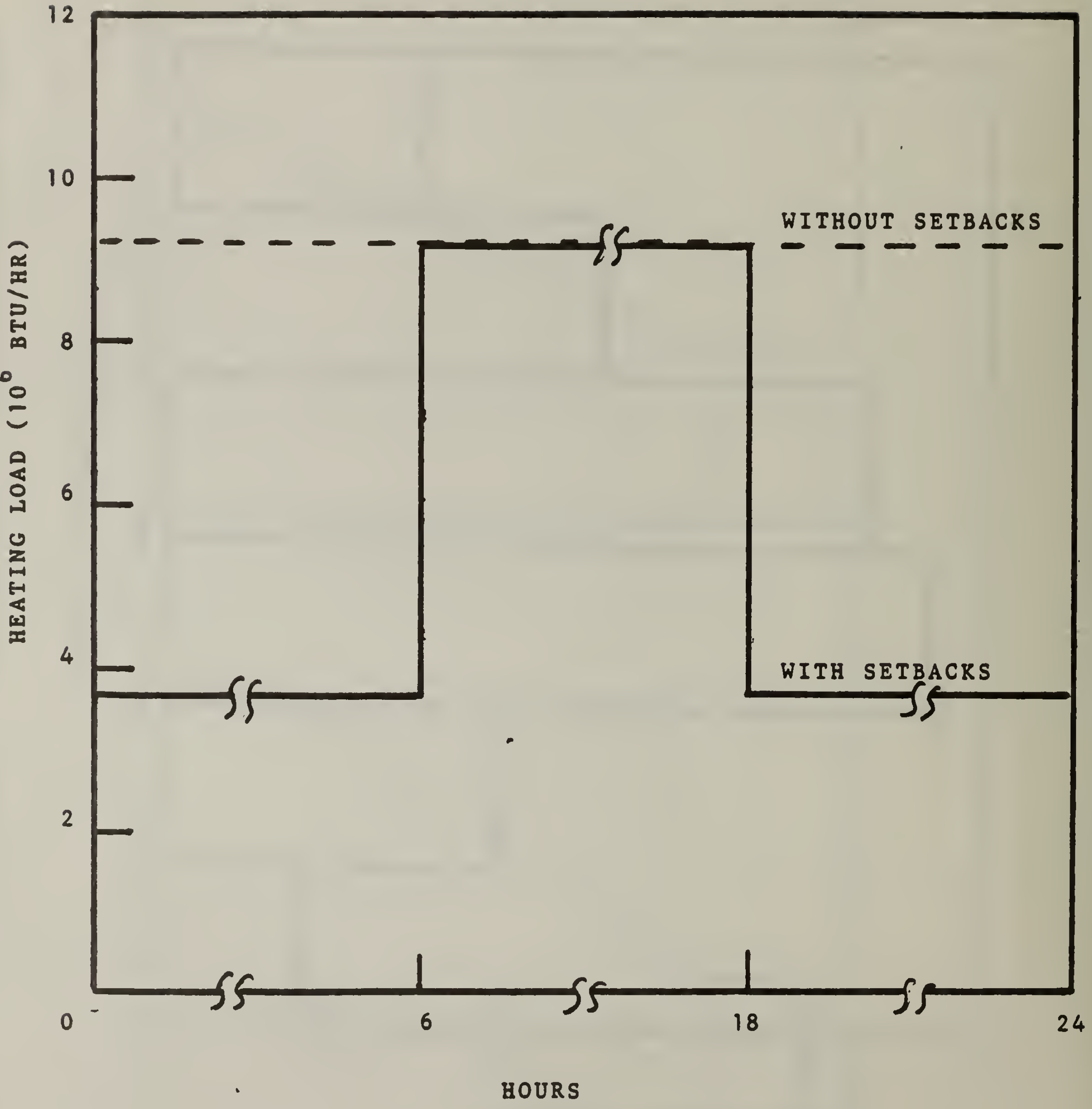


FIGURE 17 LOAD VERSUS TIME FOR A DAY WHOSE OUTDOOR AIR TEMPERATURE IS 15°F

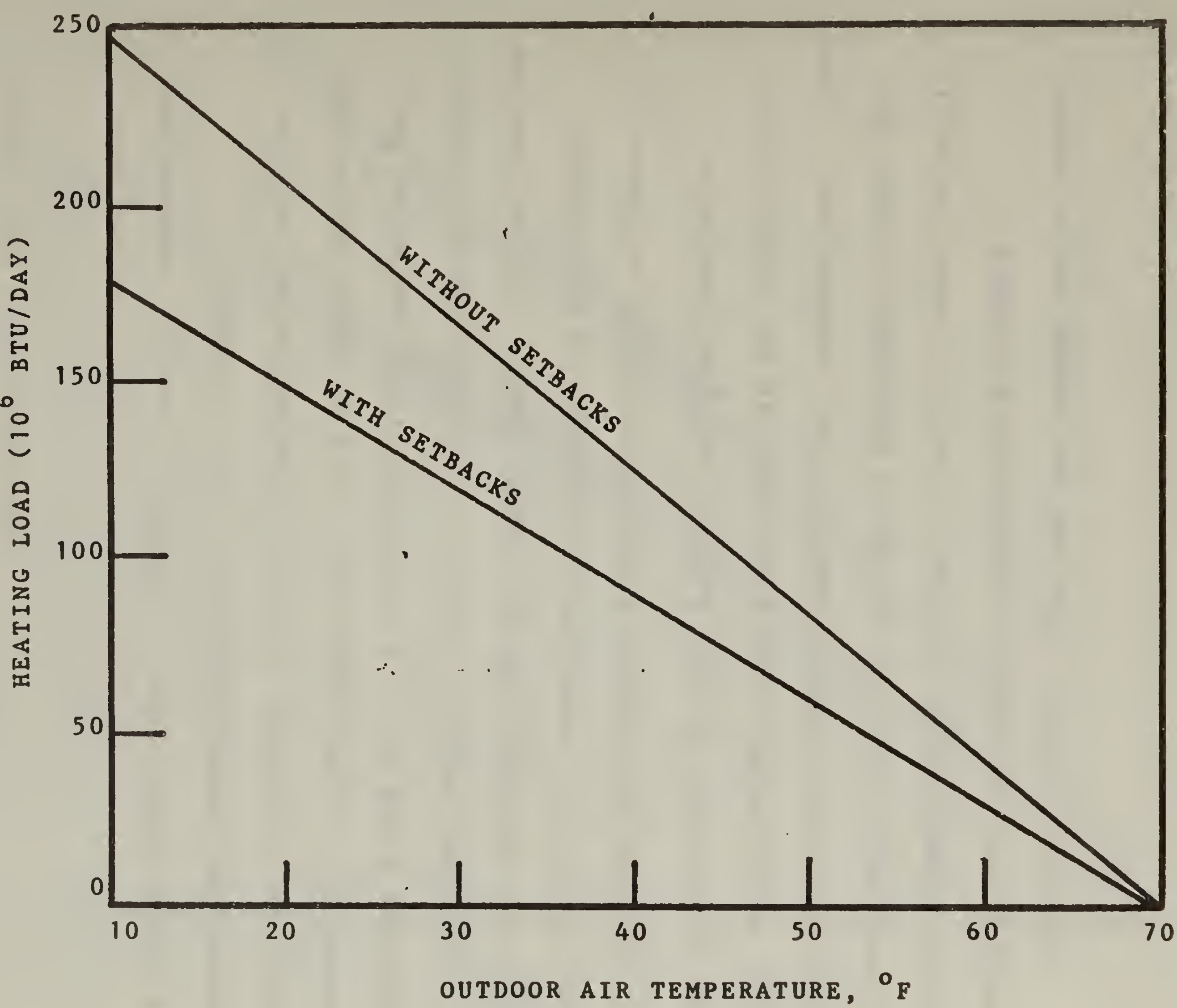


FIGURE 18 DAILY HEATING LOAD VERSUS OUTDOOR AIR TEMPERATURE

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.

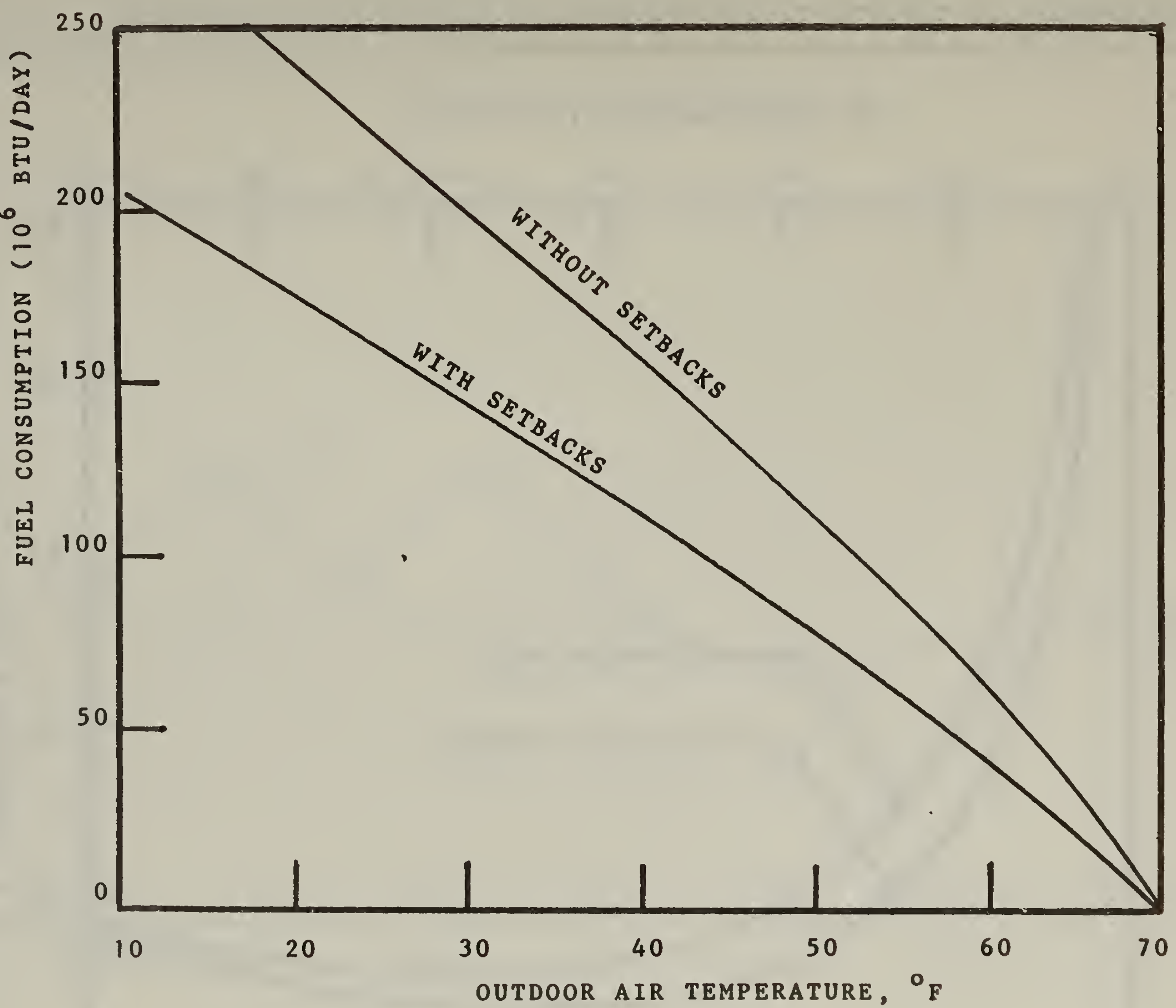


FIGURE 19 <u>DAILY FUEL CONSUMPTION VERSUS OUTDOOR AIR TEMPERATURE</u>

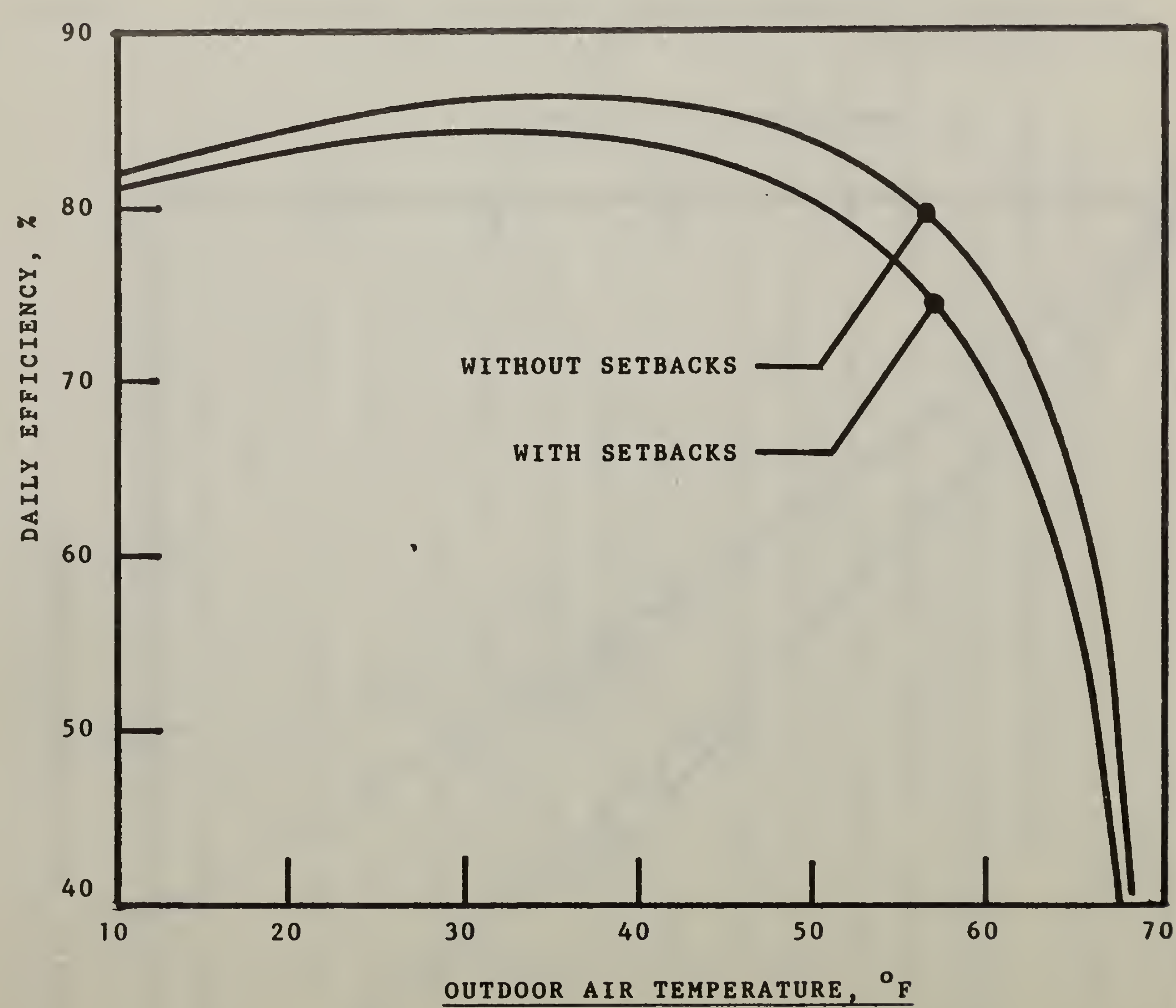


FIGURE 20 DAILY FUEL UTILIZATION EFFICIENCY VERSUS OUTDOOR AIR TEMPERATURE

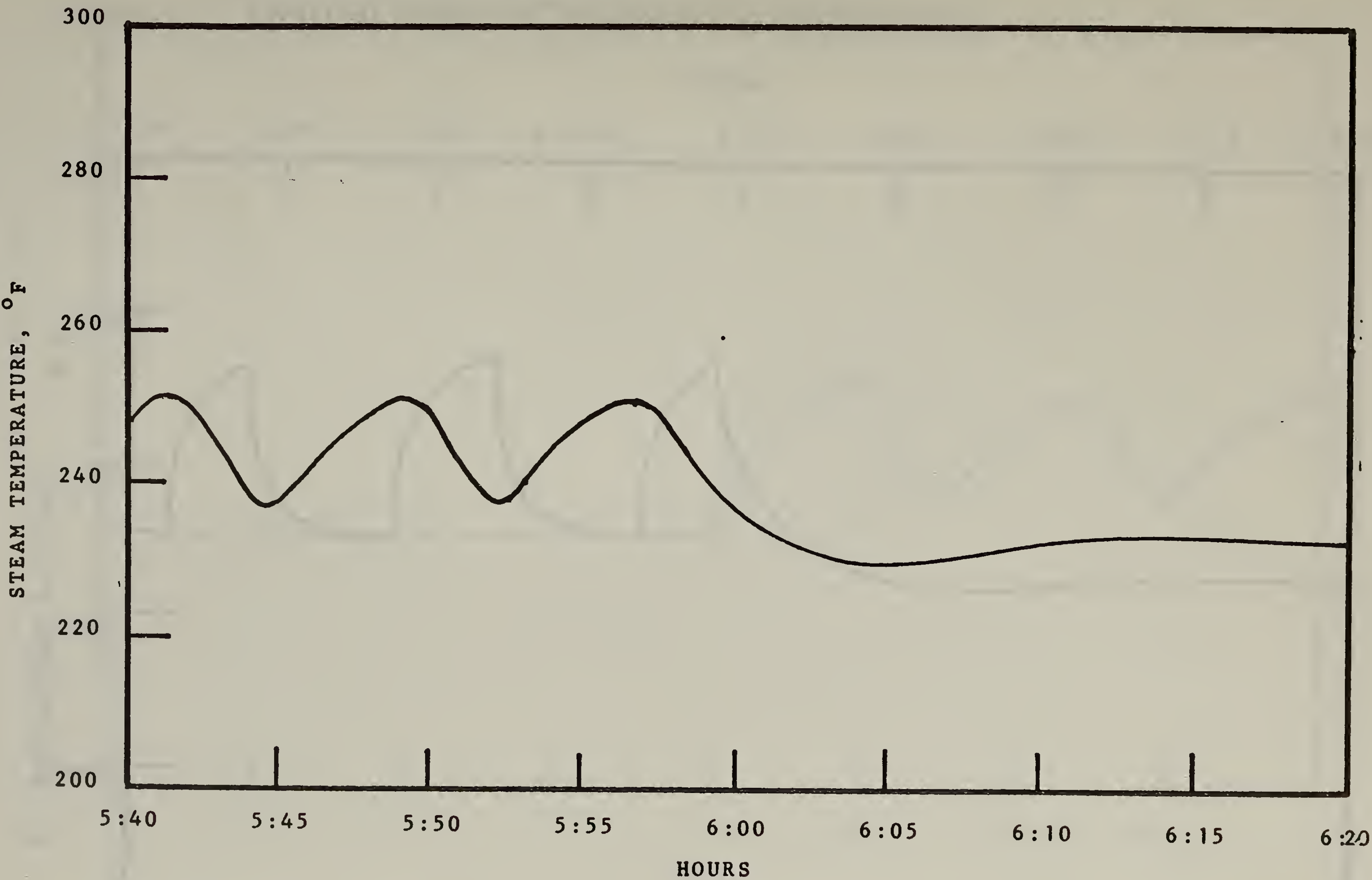


FIGURE 21 TRANSIENT STEAM TEMPERATURE AT MORNING SETUP

(FOR OUTDOOR AIR TEMPERATURE EQUAL TO 15°F)

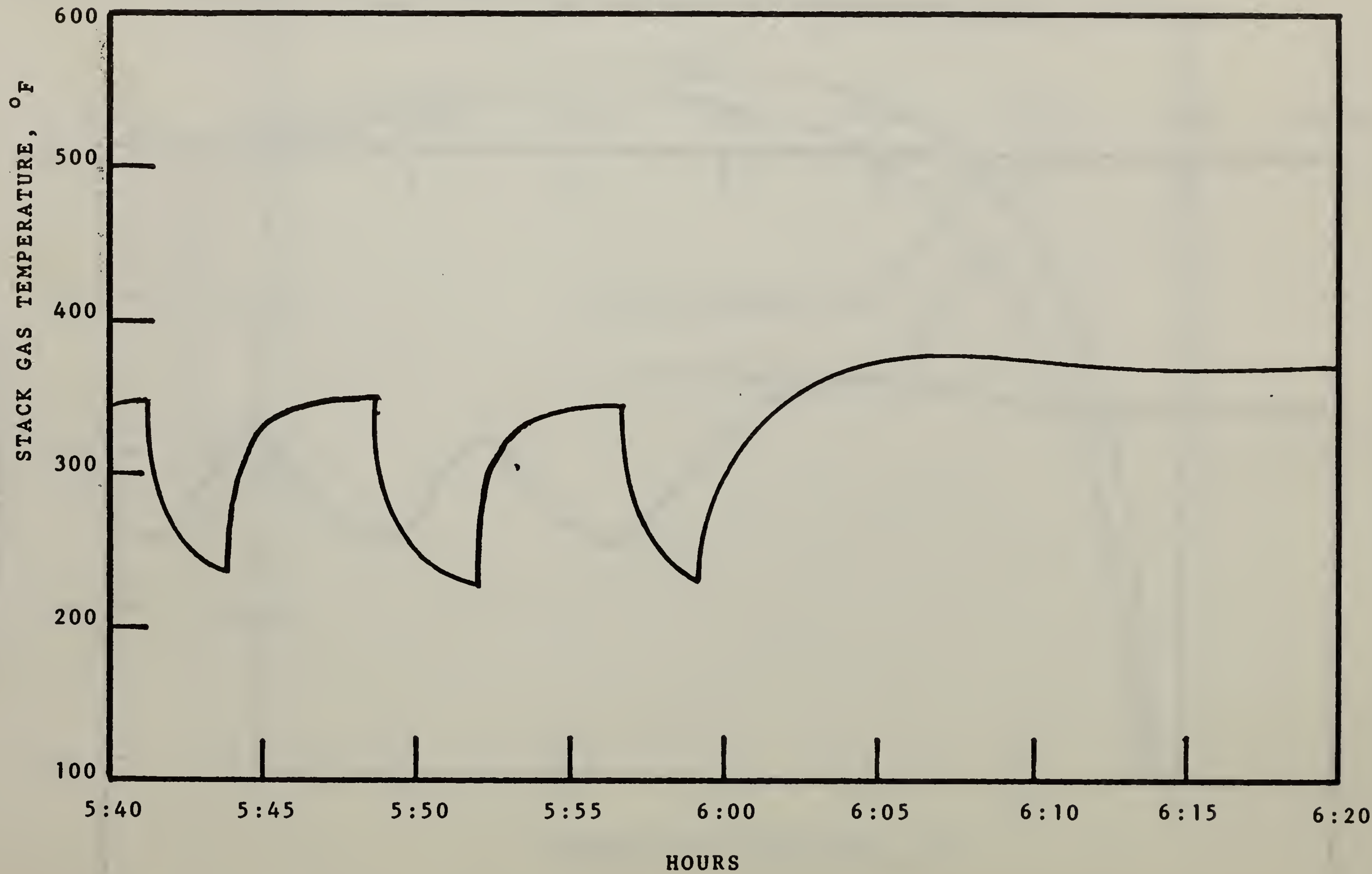


FIGURE 22 TRANSIENT STACK GAS TEMPERATURE AT MORNING SETUP
(OUTDOOR AIR TEMPERATURE EQUAL TO 15°F)

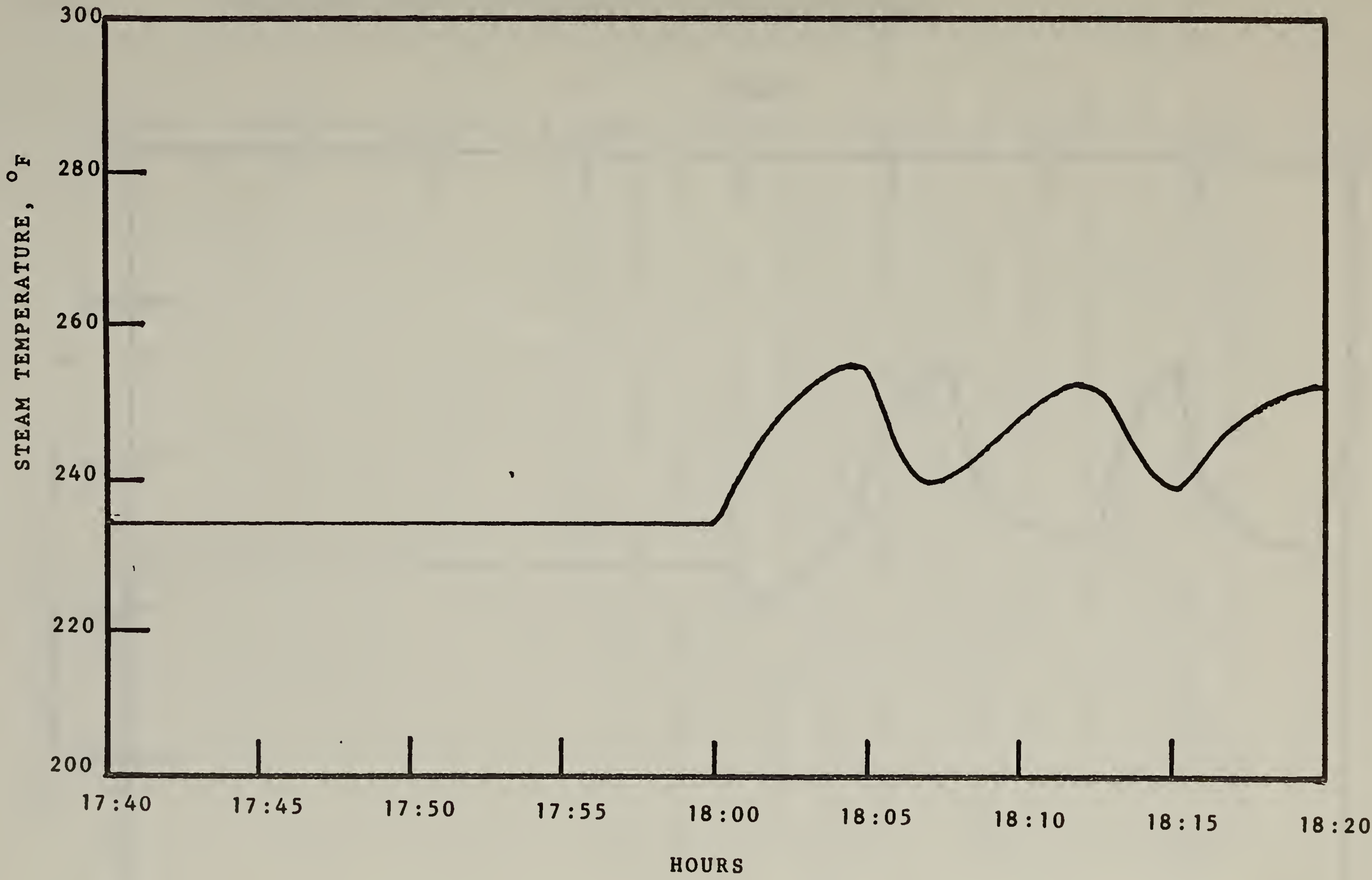


FIGURE 23 <u>TRANSIENT STEAM TEMPERATURE AT NIGHT SETBACK</u>

(FOR OUTDOOR AIR TEMPERATURE AT 15°F)

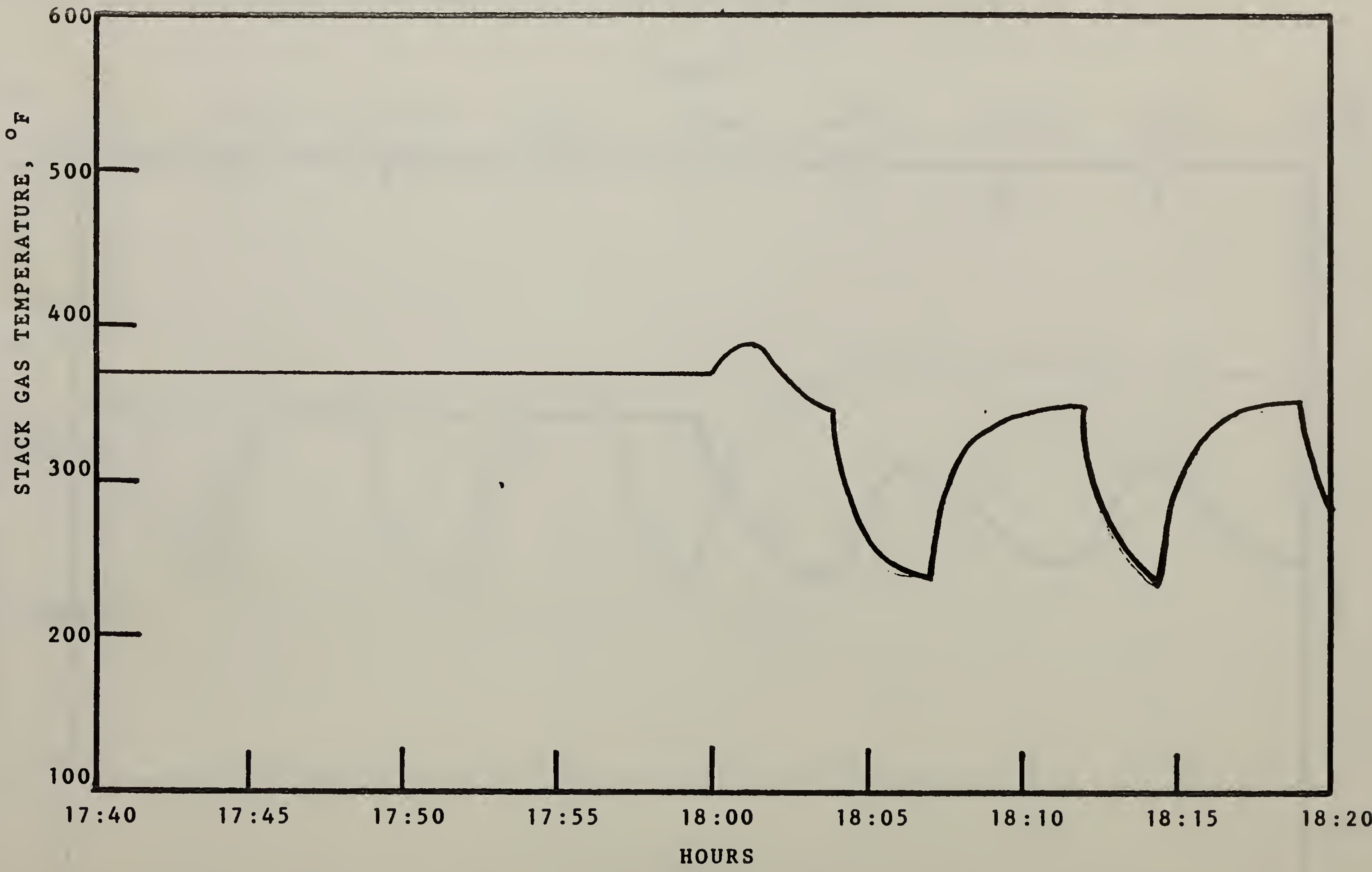


FIGURE 24 TRANSIENT STACK GAS TEMPERATURE AT NIGHT SETBACK
(FOR OUTDOOR AIR TEMPERATURE AT 15°F)

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.

BIN TEMP. ^{o}F	DAYS /BIN/YR	LOAD, 10^6BTU /DAY	FUEL, 10^6BTU /DAY	LOAD, 10^6BTU /BIN/YR	FUEL, 10^6BTU /BIN/YR
15	8.35	160.90	192,80	1,343.52	1,609.88
25	20.33	132.40	158.10	2,691,69	3,214.17
35	46.65	103.50	123.50	4,828.28	5,761.28
45	43.39	74.19	91.22	3,219.10	3,958.04
55	26.69	44.60	57.55	1,190.37	1,526.01
65	15.43	9.22	17.96	142.26	277.12
TOTAL LOAD (10^6 BTU/YEAR)				13,415.22	
TOTAL FUEL (10^6 BTU/YEAR)				16,356.50	
ANNUAL EFFICIENCY (PERCENT)				82.02	

TABLE 1 SAMPLE CALCULATION OF SEASONAL PERFORMANCE OF A BOILER WITH NIGHT SETBACKS, USING RESULTS FORM DEPAB2 RUNS

BIN TEMP. °F	DAYS /BIN/YR	LOAD, 10^6BTU /DAY	FUEL, 10^6BTU /DAY	LOAD, 10^6BTU /BIN/YR	FUEL, 10^6BTU /BIN/YR
15	8,35	229,30	273.12	1,914.66	2,280.55
25	20.33	189.07	222.62	3,843.79	4,525.86
35	46.65	148.15	172.63	6,911.20	8,053.19
45	43.39	106.20	126.96	4,608.02	5,508.79
55	26.69	63.86	77.45	1,704.42	2,067.14
65	15.43	21.26	31.99	328.04	493.61
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 DEPAB2 RUNS

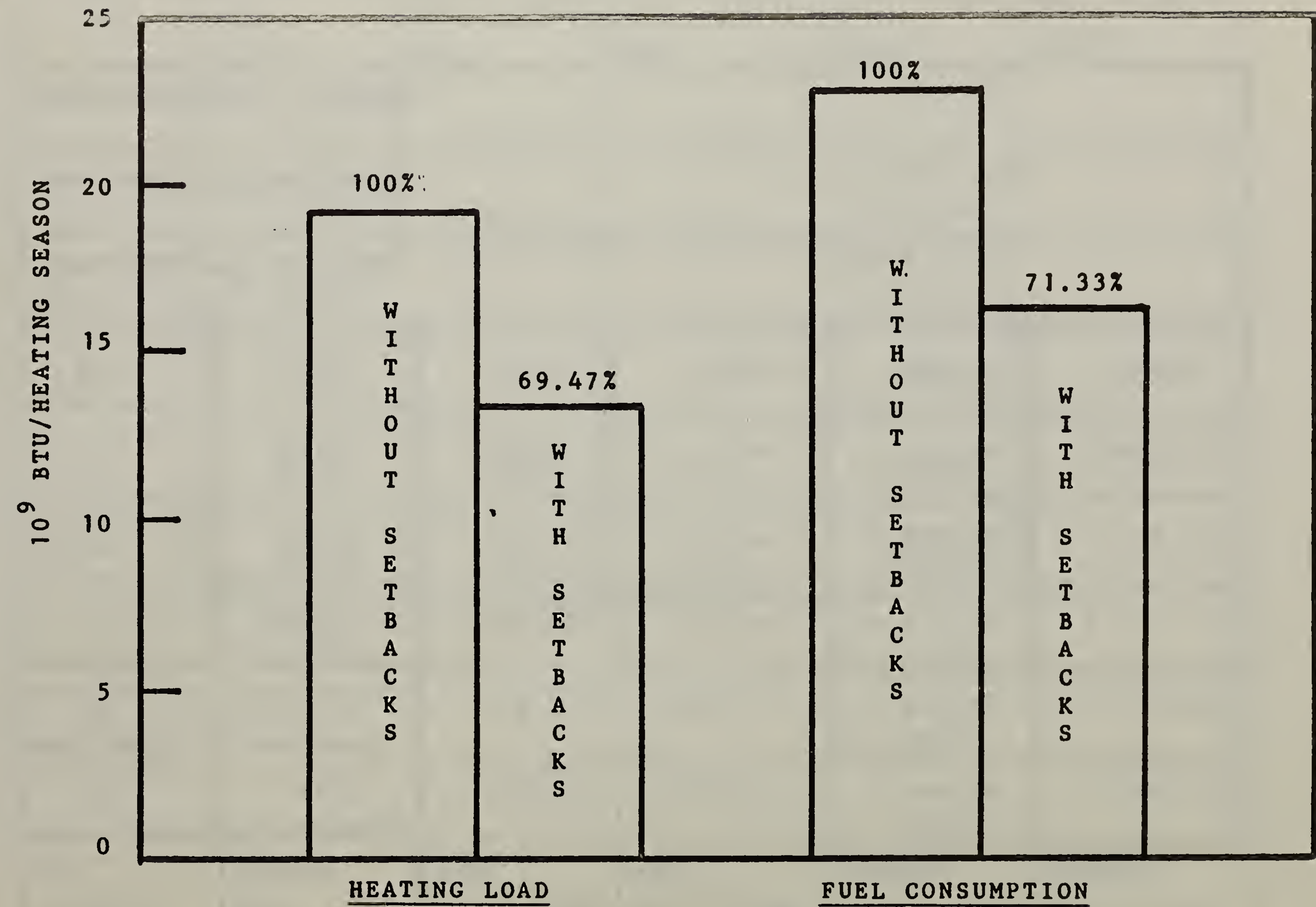


FIGURE 25 COMPARISON OF HEATING LOAD AND FUEL CONSUMPTION FOR CASES WITH AND WITHOUT SETBACKS (ON ANNUAL BASIS)

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

[1] "Combustion Equipment and Related Facilities for Non-Residential Heating Boilers." National Research Council, TR-51, 1966.

[2] Hildebrand, F. B., "Introduction to Numerical Analysis," McGraw-Hill Book Co., New York, N.Y., 1956.

[3] Hottel. H. C., and Sarofim, A. F., "Radiative Heat Transfer," McGraw-Hill Book Co., New York, N.Y., 1967

[4] McAdams, W. H., "Heat Transmission, "McGraw-Hill Book Co., New York, N.Y., 1954.

[5] Rohsenow, W. M., "A Method of Correlating Heat Transfer for Surface Boiling of Liquids," ASME Trans., Vol 73, 1951.

[6] Chi. J., "Computer Simulation of Fossil-Fuel-Fired Boilers," Proceedings of the Conference on Improving Efficiency and Performance of HVAC Equipment and Systems for Commercial and Industrial Buildings, Purdue University, April 1976.

[7] Chi, J., "Seasonal Operating Performance of Gas-Fired Hydronic Heating Systems with Certain Energy-Saving Features," International Seminar of Heat Transfer in Buildings, Dubrovnik, Yugoslavia, 1977.

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, ^{o}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^3.
*FCA = furnace air flow cross sectional area, ft^3.
*FRA = furnace refractory area, ft^3.
*FDIAM = furnace hydraulic diameter, ft.
*FSEM = furnace surface radiative emissivity,---.

Line 15 : FNA ,FNB, FNC

*FNA
*FMB
*FNC
] $=\alpha$, β and γ in $Nu = \alpha(RE)^{\beta}(PR)^{\gamma}$

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) = α value in Nu equal to $\alpha(re)^{\beta}(Pr)^{\gamma}$, for the first segment of tube,---
*TBB(1) = β value in Nu equal to $\alpha(Re)^{\beta}(pr)^{\gamma}$ for the first segment of tubes,---.

*TBC(1) = γ value in Nu 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 : TAS(NT1+1),TVL(NT1+1), TAC(NT1+1), TDI(NT1+1), TBA(NT1+1) TBB(NT1+1),TBC(NT1+1), TBE(NT1+1)

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

Line 19 : STMVL, WTAC, WTCD, WTA, WTB, WTC

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

Line 20 : SHARE, SHUFT, SHHGT, SHCAP, FNCAP, TBCAP, 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 debuging,---


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
QEXHT = exhaust gas sinsible heat loss, Btu/hr
QLTNT = exhaust gas latent heat loss, Btu/hr
TGASFN = temperature of gas at furnace exit, ^{o}F
TGASTB = temperature of gas at tube exit, ^{o}F
TTUBFN = furnace wall temperature, ^{o}F
TTUBTB = tube wall temperature, ^{o}F
TWATER = water temperature, ^{o}F
TSENSE = sonsor temperature, ^{o}F
QIPNOW = instantaneous heat input rate, Btu/hr
QUDNOW = instantaneous heat utilization rate, Btu/hr
ETANOW = instantaneous boiler efficiency value, Ratio
QIPTOT = cumulative heat input, Btu
QUDTOT = cumulative heat utilized, Btu
ETATOT = cumulative boiler efficiency, Ratio

ADDITIONAL OUTPUT FOR CYCLIC OPERATION OF BOILERS:

TIMCYC = cycling time, minutes/cycle
QUDCYC = heat utilized per cycle, Btu/cycle
QIPCYC = heat input per cycle, Btu/cycle
ETACYC = cycle efficiency, Ratio

APPENDIX D:

LISTING OF AUXILIARY SUBROUTINES

```fortran
      SUBROUTINE AIRPR(I,T,PATM,RH,W,CP,R,AM,AK)
C
C  *** CALCULATE AIR PROPERTIES
C  *** IF I=1: RELATIVE HUMIDITY GIVEN
C  *** IF I=2: SPECIFIC HUMIDITY GIVEN
C
      COMMON/WRITE/IWRITE
      IF(I.EQ.1)GOTO100
      P=W*PATM/(0.622+W)
  100 CONTINUE
      TR=T+460.
      Z=1000./TR
      IF(TR.GE.492.)GOTO10
      PSAT=EXP(0.03940*Z**3-0.2755*Z*Z-10.431*Z+19.509)
      GOTO30
   10 IF(TR.GE.672.)GOTO20
      PSAT=EXP(0.17829*Z*Z*Z-1.6896*Z*Z-5.0988*Z+13.4353)
      GOTO30
   20 PSAT=EXP(0.71692*Z**4-4.01506*Z**3+7.5568*Z*Z-14.2131*Z+16.8255)
   30 IF(I.EQ.1)GOTO110
      RH=P/PSAT
  110 CONTINUE
      IF(RH.GE.0.00001)GOTO40
      W=0.
      GOTO50
   40 PW=RH*PSAT
      W=0.622*PW/(PATM-PW)
   50 CONTINUE
      CP=0.2478786-0.4204563E-04*TR+0.5767857E-07*TR**2
     % -0.1493056E-10*TR**3
      CP=(CP+0.444*W)/(1.+W)
      R=(53.34+85.76*W)/(1.+W)
      AM=5.5029E-03+8.7157E-05*TR-2.9464E-08*TR**2
     % +6.250E-12*TR**3
      AK=-2.853E-04+3.268E-05*TR-8.253E-09*TR*TR
     % +1.239E-12*TR**3
      IF(IWRITE.LE.1)GOTO700
      WRITE(6,701)T,PATM,RH,W,CP,R,AM,AK
  701 FORMAT(/2X,'T',3X,'PATM',5X,'RH',7X,'W',8X,'CP',
     %7X,'R',8X,'AM',7X,'AK'/8(1PE9.1))
  700 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE H2OLQ(T,RO,CP,AK,AM.ST,BT)
C
C  *** CALCULATE WATER PROPERTIES
C
      DIMENSION X(5),A(5,6),B(6),C(6)
C
C   INPUT DATA:
C
C       T                TEMPERATURE                   F
C       X(I),I=1,5       T, INDEPENDENT VARIABLE       F
C       A(I,1),I=1,5     DENSITY                       LB/CUFT
C       A(I,2),I=1,5     SPECIFIC HEAT                 BTU/LB/F
C       A(I,3),I=1,5     THERMAL CONDUCTIVITY          BTU/FT-HR-F
C       A(I,4),I=1,5     DYNAMIC VISCOSITY             LB/FT-HR
C       A(I,5),I=1,5     SURFACE TENSION               LB/FT
C       A(I,6),I=1,5     EXPANSION COEFFICIENT         1/R
C
C   OUTPUT DATA:
C
C       RO               DENSITY                       LB/CUFT
C       CP               SPECIFIC HEAT                 BTU/LB-F
C       AK               THERMAL CONDUCTIVITY           BTU/FT-HR-F
C       AM               DYNAMIC VISCOSITY             LB/FT-HR
C       ST               SURFACE TENSION               LB/FT
C       BT               EXPANSION COEFFICIENT         1/R
C
      DATA NP/5/
      DATA X/32.,60.,100.,200.,500./
      DATA A/62.4,62.3,62.0,60.1,49.,
     %1.01,1.00,1.00,1.00,1.19,0.319,0.340,0.364,0.394,0.349,
     %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 H2OVP(T,RO,CP,AK,AM,HFG,BT)
C
C  *** CALCULATE STEAM PROPERTIES
C
      DIMENSION X(5),A(5,6),B(6),C(6)
C
C   INPUT DATA:
C
C  *** CALCULATE STEAM PROPERTIES
C
C
C   INPUT DATA:
C
C      T                TEMPERATURE                 F
C      X(I),I=1,5       T, INDEPENDENT VARIABLE     F
C      A(I,1),I=1,5     DENSITY                     LB/CUFT
C      A(I,2),I=1,5     SPECIFIC HEAT               BTU/LB/F
C      A(I,3),I=1,5     THERMAL CONDUCTIVITY        BTU/FT-HR-F
C      A(I,4),I=1,5     DYNAMIC VISCOSITY           LB/FT-HR
C      A(I,5),I=1,5     HEAT OF VAPORIZATION        BTU/LB
C      A(I,6),I=1,5     EXPANSION COEFFICIENT       1/R
C
C   OUTPUT DATA:
C
C      RO               DENSITY                     LB/CUFT
C      CP               SPECIFIC HEAT               BTU/LB-F
C      AK               THERMAL COONDUCTIVITY       BTU/FT-HR-F
C      AM               DYNAMIC VISCOSITY           LB/FT-HR
C      HFG              HEAT OF VAPORIZATION        BTU/LB
C      BT               EXPANSION CNEFDICHENT       1/R
C
      DATA NP/5/
      DATA X/32.,100.,200.,300.,500./
      DATA A/3.03E-4,2.85E-3,2.97E-2,0.155,1.48,
     %0.44,0.4488,0.4791,0.5508,0.968,
     %0.01,0.0116,0.0140,0.0172,0.0306,
     %0.0192,0.0229,0.0283,0.0331,0.0427,
     %1075.3,1037.1,977.9,910.0,714.3,
     %2.03E-3,1.79E-3,1.52E-3,1.316E-3,1.042E-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)
      HFG=C(5)
      BT=C(6)
      RETURN
      END
```

```
      SUBROUTINE PRDPR(T,PCO2,PH2O,PO2,PN2,PSO2,
     %AMM,AKK)
C
C  *** CALCULATE VISCOSITY AND CONDUCTIVITY OF PRODUCTS
C
      DIMENSION X(11),A(11),B(11),AM(5),AK(5)
      DATA X/-10.,260.,440.,620.,800.,1070.,
     %1520.,2420.,3140.,3500.,4160./
      DATA A/0.0387,0.0553,0.0646,0.073,0.0806,0.0911,
     %0.1062,0.1320,0.1500,0.1583,0.1710/
      DATA B/0.01287,0.01944,0.02333,0.02692,0.03022,
     %0.03483,0.04178,0.05348,0.0612,0.0646,0.0709/
      DATA AM/0.889,0.685,1.123,0.964,0.889/
      DATA AK/0.925,0.906,1.037,0.983,0.925/
      NP=11
      AMM=PCO2*AM(1)+PH2O*AM(2)+PO2*AM(3)+
     %PN2*AM(4)+PSO2*AM(5)
      AKK=PCO2*AK(1)+PH2O*AK(2)+PO2*AK(3)+
     %PN2*AK(4)+PSO2*AK(5)
      AMM=AMM*TAB1(NP,X,A,T)
      AKK=AKK*TAB1(NP,X,B,T)
      RETURN
      END
```

```
      FUNCTION CPF(T1,T2,PCO2,PH2O,PO2,PSO2,PN2)
C
C  *** INPUT: (T1) TEMPERATURE, DEG R, (T2)
C TEMPERATURE, DEG R, (PCO2) NO. MOLES CO2,
C (PH2O) NO. MOLES H2O, (PO2) NO. MOLES O2,
C (PSO2) NO. MOLES SO2, (PN2) NO. MOLES N2
C
C  *** OUTPUT: (CP) SPECIFIC HEAT OF PROD,
C BTU/LB-DEG R
C WHERE CPF IS THE SPECIFIC HEAT FUNCTION
C
      DIMENSION C(6,2)
      DIMENSION A(30),B(30),AA(30),BB(30)
      DATA A/4.2497678,-6.912652E-3,3.1602134E-5,-2.9715432E-8,
     %9.510358E-12,2.1701,1.0378115E-2,-1.0733938E-5,6.3459175E-9,-1.628
     %0701E-12,4.1565016,-1.7244334E-3.5.6982316E-6,-4.5930044E-9,1.4233
     %654E-12,3.6916148,-1.3332552E-3,2.65031E-6,-9.768834E-10,-9.977223
     %4E-14,3.7189946,-2.5167288E-3,8.5837353E-6,-8.2998716E-9,2.708218E
     %-12,3.2257132,5.6551207E-3,-2.4970208E-7,-4.2206766E-9,2.1392733E-
     %12/
      DATA B/1.1795744,1.0950594E-2,-4.062213E-6,7.1370281E-10,
     %-4.7490353E-14,4.4129266,3.1922896E-3,-1.297823E-6,2.4147446E-10
     %,1.6742986E-14,2.6707532,3.0317115E-3,-8.535157E-7,1.1790853E-10,
     %-6.1973568E-15,2.8345761,1.5976316E-3,-6.2566254E-7,1.1315849E-
     %10,-7.689707E-15,3.5976129,7.8145603E-4,-2.238667E-7,4.2490159E
     %-11,-3.3460204E-15,5.1982451,2.0595095E-3,-8.6254450E-7,
     %1.6636523E-10,-1.1847837E-14/
C
C  *** MODIFY A AND B FROM K UNITS TO R UNITS
C
      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))
   10 CONTINUE
C
C  *** DETERMINE TEMP RANGE OF T1 AND T2
C
      IF(T1.GT.1800.)GO TO 25
      IF(T2.GT.1800.)GO TO 15
C
C  *** T1 AND T2 ARE LESS THAN 1800 R
C
      DO 20 I=1,6
   20 C(I,1)=0.
      DO 30 I=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
   35 CONTINUE
      C(I,1)=C(I,1)*1.98726/(T2-T1)
   30 CONTINUE
      CPF=(PCO2*C(2,1)+PH2O*C(3,1)+PN2*C(4,1)
     %+PO2*C(5,1)+PSO2*C(6,1))/(PCO2*44.
     %+PH2O*18.+PN2*28.+PO2*32.+PSO2*64.)
      GO TO 99
```

```
C
   15 CONTINUE
C
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
      JJ=M+J
      C(I,1)=C(I,1)+AA(JJ)*(TM**J-T1**J)/J
      C(I,2)=C(I,2)+BB(JJ)*(T2**J-TM**J)/J
   37 CONTINUE
      C(I,1)=(C(I,1)+C(I,2))*1.98726/(T2-T1)
   32 CONTINUE
      CPF=(PCO2*C(2,1)+PH2O*C(3,1)+PN2*C(4,1)
     %+PO2*C(5,1)+PSO2*C(6.1))/(PCO2*44.
     %+PH2O*18.+PN2*28.+PO2*32.+PSO2*64.)
      GO TO 99
C
   25 CONTINUE
      IF(T2.LT.1800.)GO TO 55
C
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 31 I=1,6
      M=5*(I-1)
      DO 36 J=1,5
      JJ=M+J
      C(I,2)=C(I,2)+BB(JJ)*(T2**J-T1**J)/J
   36 CONTINUE
      C(I,2)=C(I,2)*1.98726/(T2-T1)
   31 CONTINUE
      CPF=(PCO2*C(2,2)+PH2O*C(3,2)+PN2*C(4,2)
     %+PO2*C(5,2)+PSO2*C(6,2))/(PCO2*44.
     %+PH2O*18.+PN2*28.+PO2*32.+PSO2*64.)
      GO TO 99
C
   55 CONTINUE
C
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
      JJ=M+J
      C(I,1)=C(I,1)+AA(JJ)*(TM**J-T2**J)/J
      C(I,2)=C(I,2)+BB(JJ)*(T1**J-TM**J)/J
   39 CONTINUE
      C(I,1)=(C(I,1)+C(I,2))*1.98726/(T1-T2)
   34 CONTINUE
      CPF=(PCO2*C(2,1)+PH2O*C(3,1)+PN2*C(4,1)
     %+PO2*C(5,1)+PSO2*C(6,1))/(PCO2*44.
     %+PH2O*18.+PN2*28.+PO2*32.+PSO2*64.)
C
   99 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE PP(PTOTAL,CARB,HYDR,OXYG,XNTR,SULF,EXAIR,
     *PCO2,PH2O,PSO2,PO2,PN2,RATF,RPTF,RWTF)
C
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
C  *** OUTPUT: (PPCO2) PARTIAL PRES CO2, ATM, (PPH2O)
C PARTIAL PRES H2O, ATM, (AFRTT) THEORETICAL AIR FUEL
C RATIO, (PCO2) NO. MOLES CO2, (PH2O) NO. MOLES H2O, (PO2)
C NO. MOLES O2, (PSO2) NO. MOLES SO2, (PN2) NO. MOLES N2,
C (UPRD) UNIT PARTIAL PRES OF PRODUCTS, LB PROD/LB FUEL
C
C  *** MOLES OF O AND N REQD TO BE ADDED
C
      RO0=2.*CARB+0.5*HYDR+2.*SULF-OXYG
      RN0=3.76*RO0
C
C  *** MOLES OF CO2, H2O, O2, SO2 AND N2 IN PRODUCTS
C
      PCO2=CARB
      PH2O=0.5*HYDR
      PO2=0.3*RO0*EXAIR
      PSO2=SULF
      PN2=0.5*XNTR+0.5*RN0*(1.+EXAIR)
C
C  *** WT OF FUEL, AIR AND PRODUCTS
C
      WTF=12.*CARB+HYDR+16.*OXYG+14.*XNTR+32.*SULF
      WTA=(16.*RO0+14.*RN0)*(1.+EXAIR)
      WTP=(44.*PCO2+18.*PH2O+32.*PO2+64.*PSO2+28.*PN2)
      WTW=18.*PH2O
C
C  *** COMPUTE PPCO2, PPH2O, AFRTT AND UPRD
C
      AMULT=PTOTAL/(PCO2+PH2O+PO2+PSO2+PN2)
      PCO2=PCO2*AMULT
      PH2O=PH2O*AMULT
      PSO2=PSO2*AMULT
      PO2=PO2*AMULT
      PN2=PN2*AMULT
      RATF=WTA/WTF
      RPTF=WTP/WTF
      RWTF=WTW/WTF
C
      RETURN
      END
```

```
      FUNCTION TAFF(HHV,RWTF,UPRD,PCO2,PH2O,PO2,
     %PSO2,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, (PCO2) NO. MOLES CO2, (PH2O) NO. MOLES
C H2O, (PO2) NO. MOLES O2, (PSO2) NO. MOLES SO2,
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
      HVV=HHV-1050.*RWTF
      TAF1=HVV/UPRD/CP1+T0
    6 CP=CPF(TAF1,T0,PCO2,PH2O,PO2,PSO2,PN2)
      TAF2=HVV/UPRD/CP+T0
      T=ABS((TAF1-TAF2)/TAF1)
      TAF1=TAF2
      IF(T.GT.PC)GO TO 6
      TAFF =TAF1
C
      RETURN
      END
```

```
      SUBROUTINE GF(BTUHK,HFUEL,CPFUEL,TFUEL,TAIR,RATF,RPTF,
     %WFUEL,WAIR,WGAS)
C
C  *** CALCULATE BOILER FUEL/AIR FFLOW
C
C   INPUT DATA:
C      BTUHK   KBTUH INPUT RATE
C      HFUEL   FUEL HEATING VALUE, BTU/LB
C      CPFUEL  FUEL SPECIFIC HEAT, BTU/LB/F
C      RATF    MASS RATIO OF AIR TO FUEL, ---
C      RPTF    MASS RATIO OF PRODUCT TO FUEL, ---
C      TFUEL   FUEL TEMPERATURE, F
C      TAIR    AIR TEMPERATURE, F
C   OUTPUT DATA:
C      WFUEL   FUEL FLOW RATE, LB/HR
C      WAIR    AIR FLOW RATE, LB/HR
C      WGAS    TOTAL GAS FLOW RATE, LB/HR
C
      COMMON/WRITE/IWRITE
      IF(IWRITE.EQ.2)WRITE(6,702)BTUHK,HFUEL,CPFUEL,RATF,RPTF
  702 FORMAT(/2X,3HGF:/2X,5HBTUHK,6X,5HHFUEL,
     %6X,6HCPFUEL,5X,4HRATF,7X,4HRPTF/5(1PE11.3))
      HHV=HFUEL+CPFUEL*(TFUEL-TAIR)
      WFUEL=1000.*BTUHK/HFUEL
      WAIR=RATF*WFUEL
      WGAS=RPTF*WFUEL
      WRITE(6,710)TFUEL,TAIR,WFUEL,WAIR,WGAS
  710 FORMAT(2X,5HTFUEL,6X,4HTAIR,7X,5HWFUEL,6X,4HWAIR,7X,4HWGAS/
     %5(1PE11.3))
      RETURN
      END
```

```
      SUBROUTINE BG(BTUHK,EXAIR,HFUEL,CPFUEL,
     *TFUEL,THAIR,WFUEL,WAIR)
C
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
```

```
      FUNCTION RENB(AMAS,AMU,AC,D)
C
C  *** CLACULATE REYNOLDS NUMBER
C
      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)
C
C  *** CALCULATE PRANDTL NUMBER.
C
      COMMON/WRITE/IWRITE
      IF(IWRITE.LE.1)GOTO704
      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)GOTO700
      WRITE(6,702)PRNB
  700 RETURN
  702 FORMAT(/2X,5HPRNB=,1PE11.3)
      END
```

```
      FUNCTION AIRFHT(T1,T2,AL)
C
C  *** CALCULATE AIRSIDE FREE CONVECTION HEAT TRANSFER COEFFICIENT
C
C   INPUT DATA:
C      T1         SURFACE TEMPERATURE                          F
C      T2         AIR TEMPERATURE                              F
C      AL         CHARACTERISTIC LENGTH                        FT
C
C   OUTPUT DATA:
C      AIRFHT     AIR FREE CONVECTION HT TRANCFER COEFF            BTU/SQFT-HR-F
C
      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(PPCO2,PPH2O,XL,TG)
C
C  *** INPUT:(PPCO2) PARTIAL PRES CO2, ATM, (PPH2O)
C PARTIAL PRES H2O, ATM, (XL) LENGTH OF COMBUSTION
C CHAMBER, FT, (TG) RADIATING GAS TEMP, DEG R
C
C  *** OUTPUT: (GE) GAS EMISSIVITY
C WHERE GEF IS THE GAS EMISSIVITY FUNCTION
C
C  *** SELECT GAS EMISSIVITY CONSTANTS
C C1 AND C2
C
      XX=(PPCO2+PPH2O)*XL
      IF(XX.GT..2)GO TO 4
      C1=406.9
      C2=0.62
      GO TO 6
    4 C1=287.
      C2=0.4
    6 CONTINUE
C
C  *** COMPUTE GAS EMISSIVITY
C
      GEF=XX**C2*C1/TG
C
      RETURN
      END
```

```
      FUNCTION GS(AT,CS,GE,SE)
C
C  *** CALCULATE GAS/SINK EXCHANGE AREA
C
      GS=1./SE+1./(CS*GE)-1.
      GS=AT/GS
      RETURN
      END
```

```
      FUNCTION OVHT(I,AO,AP,AF,AI,ALFO,ALFI,TP,AK,FEE)
C
C  *** CALCULATE OVERALL HEAT TRANSFER COEFFICIENT
C  *** I=1: OUTSIDE SURFACE
C  *** I=2: INSIDE SURFACE
C  *** I=3: OVERALL
C
      COMMON/WRITE/IWRITE
      IF(IWRITE.LE.1)GOTO704
      WRITE(6,706)I,AO,AP,AF,AI,ALFO,ALFI,TP,AK,FEE
  704 CONTINUE
  706 FORMAT(/2X,5HOVHT:/2X,1HI,2X,2HAO,9X,2HAP,9X,2HAF,9X,
     %2HAI/I3,4(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+0.5*AA+AO/(AI*ALFI)
      GOTO 100
   10 ALF=AI*TP/(2.*AP*AK)+1./ALFI
  100 OVHT=1./ALF
      IF(IWRITE.LE.1)GOTO700
      WRITE(6,702)OVHT
  700 RETURN
  702 FORMAT(/2X.5HOVHT=,1PE11.3)
      END
```

```
      FUNCTION TAB1(NP,X,Y,X1)
C
C  *** PURPOSE : FROM TABULATED Y VS X VALILES
C      TO DETERMINE Y(X1) VALUE
C
C  *** WRITTEN BY: JOSEPH CHI                                   80FEB20
C
C  *** INPUT/OUTPUT LIST:
C
C      NP   NUMBER OF DATA POINTS
C      X    DATA POINT INDEPENDENT VARIABLES
C      Y    DATA POINT DEPENDENT VARIABLES
C      TAB1 OUTPUT DEPENDENT VARIABLE
C      X1   INPUT INDEPENDENT VARIABLE
C
      DIMENSION X(NP),Y(NP)
C  *** SET OUT OF RANGE Y1(X1) VALUES
      XMIN=X(1)
      XMAX=X(NP)
      IF(X1.GT.XMIN)GOTO10
      Y1=Y(1)
      GOTO100
   10 IF(X1.LT.XMAX)GOTO20
      Y1=Y(NP)
      GOTO100
C  *** IFTPOLATE FOR Y1(X1) VALUE
   20 I=1
   40 IF (X1.GT.X(I))GOTO30
      DXT=X(I)-X(I-1)
      DYT=Y(I)-Y(I-1)
      RDXT=1./DXT
      DYODX=DYT*RDXT
      DX=X1-X(I-1)
      Y1=Y(I-1)+DX*DYODX
      GOTO100
   30 I=I+1
      GOTO40
  100 TAB1=Y1
      RETURN
      END
```

```
      FUNCTION STSATT(PG)
C
C     CALCULATE STEAM SATURATION T FROM P
C
      DATA AG,BG,CG,DG,EG,FG,AA,BB,TFR/90.41858,
     +-16041.139,-10.48695,0.0046831,0.270452,
     +1179.51,132.,570.,459.67/
      IF(PG.LE.0)GOTO999
      PLOG=ALOG(PG)
      TR=0.43429448*AA*PLOG+BB
      DO10ITR=1,30
      TRO=TR
      C=ALOG(ABS(FG-TRO))
      F=AG+BG/TRO+CG*ALOG(TRO)+DG*TRO+EG*((FG-TRO)*C/TRO)-PLOG
      FT=-BG/TRO**2+CG/TRO+DG
      IF(ABS(EG).GE.1.E-20)FT=FT-EG*(1./TRO+FG*C/TRO**2)
      TR=TRO-F/FT
      IF(ABS(TR-TRO).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 ROGTP(ROG,TG,PG)
C
C     CALCULATE T AND P FROM SATURATION VAPOR DENSITY
C
      DIMENSION RO(21),T(21)
      DATA RO/0.00058679,0.00285714,0.01031034,0.01992032,
     +0.02973536,0.03731343,0.04319654,0.05138362,0.06124824,
     +0.0723275,0.08497621,0.11560694,0.15451174,0.20329335,
     +0.26371306,0.33772374,0.42753313,0.53587697,0.90818273,
     +1.4790711,3.7355248/
      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
      TG=TAB1(NP,RO,T,ROG)
      PG=STSATP(TG)
      RETURN
      END
```

```
      FUNCTION STSATP(TG)
C
C     CALCULATE STEAM SATURATION PRESSURE FROM TEMPERATURE
C
      DATA AG,BG,CG,DG,EG,FG,EEP,TC,TFR/90.41858,
     +-16041.139,-10.48695,0.0046831,0.270452,
     +1179.51,2.7182818,1165.11,459.67/
      T=TG+TFR
      IF(T.GT.TC)GOTO999
      C=ALOG(ABS(FG-T))
      STSATP=EEP**(AG+BG/T+CG*ALOG(T)+DG*T+EG*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)
C
C  *** CALCULATES SINGLE-PHASE PRESSURE DROP
C
      COMMON/WRITE/IWRITE
      IF(IWRITE.LE.1)GOTO704
      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/
     %4(1PE11.3))
      AAT=0.046
      BBT=0.2
      AAL=16.
      BBL=1.
      G=AMAS/AC
      TALF=AF
      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=(3.330868E-11)*F*V*AL*G*G/D
      IF(IWRITE.LE.1)GOTO700
      WRITE(6,702)SGDP
  700 RETURN
  702 FORMAT(/2X,5HSGDP=,1PE11.3)
      END
```

```
      SUBROUTINE WATPR(TW,WATRO,WATK,WATM,WATHFG,WATCP)
C
C  *** CALCULATE WATER PROPERTIES
C
      COMMON/WRITE/IWRITE
      DIMENSION ARO(5),AK(5),AM(5),AHFG(5)
      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,
     %-0.88613E-08,0.41387E-11/
      DATA AM/0.79424E03,-0.47589E01,0.10622E-01,
     %-0.10416E-04,0.37690E-08/
      DATA AHFG/0.31514E04.-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=459.67
      TWR=TW+TFR
      WATRO=0.
      WATK=0.
      WATM=0.
      WATHFG=0.
      IF(TW.LE.32.)GOTO100
      DO10I=1,5
      J=I-1
      AA=TWR**J
      WATRO=WATRO+ARO(I)*AA
      WATK=WATK+AK(I)*AA
      WATM=WATM+AM(I)*AA
   10 WATHFG=WATHFG+AHFG(I)*AA
      WATCP=1.
      GOTO200
  100 WATRO=19.
      WATK=0.82
      WATM=1.E25
      WATHFG=1219.
      WATCP=0.46
  200 IF(IWRITE.LE.1)GOTO700
      WRITE(6,702)TW,WATRO,WATK,WATM,WATHFG,WATCP
  700 RETURN
  702 FORMAT(2X,2HTW,9X,5HWATRO,6X,4HWATK,7X,
     %4HWATM,7X,6HWATHFG,5X,5HWATCP/6(1PE11.3))
      END
```

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10. SUPPLEMENTARY NOTES

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

11. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)*

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.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

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

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