

APPENDIX BCOMPARTMENT DIFFERENTIAL PRESSURE ANALYSIS DESCRIPTION

The computer codes COPDA, FLUD and COTTAP4 were used to evaluate compartment differential pressure. This appendix describes the computational procedure and the analytical techniques used in FLUD. The analytical basis for COPDA is described in Reference 6B-4 and the analytical basis for COTTAP4 is described in Reference 3.6-10. The set-up of initial conditions, the determination of the thermodynamic state point at subsequent time increments, and computation of energy and mass transport between one time step is discussed in Sections 6B.1, 6B.2 and 6B.3 for FLUD. Selection was made of the control volume and flow path configuration that resulted in the best representation of the pressure transients in the compartments along the flow paths from the break.

6B.1 FLUD Calculational Procedure

The major differences between FLUD and COPDA (Ref. 6B-4) are the use of steam table curve fits (Section 6B.3) instead of table look-ups and the equation of state which is a first-order virial expansion (discussed in 6B.1.1). The fluid flow equations (compressible equations, HEM model and integrated momentum equation) used in COPDA have been reproduced in the FLUD Code. It may be observed from the FLUD flowchart in Fig. 6B-1 that the calculational procedures for FLUD and COPDA are very similar.

6B.1.1 Equation of State

In this section we describe how FLUD determines the thermodynamic state for each compartment in a system of interconnected compartments.

Our thermodynamic system (compartment) is assumed to be in equilibrium. The states assumed by the air-steam-water mixture can be described in terms of thermodynamic coordinates P, V, and T referring to the mixture as a whole. The equation of state is derived from a first order virial expansion as presented in Ref. 6B-1. Using the molecular theory of gases, the following equation of state for an air-steam mixture is obtained assuming negligible air-steam molecular interaction:

$$P = (M_a R_a + M_s R_s) \frac{T}{V} + \left( \frac{M_s}{V} \right)^2 R_s T B_s(T), \quad (1bf / ft^2) \quad (\text{Eq. 6B-1})$$

where the temperature dependence of the second virial coefficient for steam  $B_s(T)$  is given by<sup>2</sup>

$$B_s(T) = 0.0330 - \frac{75.3137}{T} 10^{3.2659} / (T^2 \times 10^{-5} + 1.1308) \quad (\text{Eq. 6B-2})$$

Eq. 6B-1 can be rewritten as the sum of the partial pressure of air  $P_a$  and the partial pressure of steam  $P_s$  where

$$P_a = \frac{M_a}{V} R_a T, (1bf / ft^2) = 0.37043 \frac{T}{v_a}, (psia) \quad (\text{Eq. 6B-3})$$

and

$$P_s = \frac{M_s}{V} R_s T \left[ 1 + \frac{M_s}{V} B_s(T) \right], (1bf / ft^2) \quad (\text{Eq. 6B-4})$$

Eq. 6B-4 compares well with the steam tables.<sup>2</sup> For example, the relative error in Eq. 6B-4 is less than 1% for saturated steam at temperatures less than 570°F.

#### 6B.1.2 Compartment Thermodynamic State

At any time, the total internal energy  $E$ , the air mass  $M_a$ , and the vapor mass  $M_v$  have known values for each compartment. Vapor is defined as a homogeneous mixture of steam and water in unknown proportions.

The internal energy is a function of as many thermodynamic coordinates as are necessary to specify the state of the system. Therefore, for known air and vapor masses and because the compartment volume is originally specified, the compartment internal energy can be expressed as a function of temperature only:

$$E = E(T) \quad (\text{Eq. 6B-5})$$

At the saturation temperature  $T_o$ , there is a discontinuous change in the slope of  $E(T)$  due to a phase change in the compartment atmosphere. Associated with  $T_o$  is the compartment saturation energy  $E_o = E(T_o)$ . Equation 6B-5 has two branches: (1) a two-phase branch where  $E < E_o$  and  $T < T_o$  and (2) a superheat branch where  $E > E_o$  and  $T > T_o$ . Along the two-phase branch the vapor portion of the atmosphere has a non-zero water mass component, while along the superheat branch the vapor contains no water.

Having examined the behavior of  $E(T)$ , we now proceed to solve EQ. 6B-5 for the compartment temperature,  $E$  being known.  $v_{sat}$ ,  $e_{sat}$  and  $v_w$ ,  $e_w$  represent the specific volumes and specific internal energies of saturated steam and water respectively. The dependence of these quantities on temperature is determined empirically from steam

table curve fits described in Section 6B-3.  $E_o$  is calculated to determine on which branch of  $E(T)$  the compartment temperature lies. At compartment saturation, the steam mass  $M_s$  is identical to  $M_v$  and the specific volume of the steam is just  $v_{sat}(T_o)$ . Thus,

$$V = M_v v_{sat}(T_o) \quad (\text{Eq. 6B-6})$$

The above equation is easily solved to  $T_o$  by utilizing the inverse of the function  $v_{sat}(T_o)$ , which is also a steam table curve fit where  $T_o = T_{sat}(V/M_v)$ . The saturation internal energy for the compartment is then given by

$$E_o = M_a c_{va} T_o + M_v e_{sat}(T_o) \quad (\text{Eq. 6B-7})$$

where  $c_{va} = 0.1725$  Btu/lbm $^{\circ}$ R is the specific heat at constant volume for air averaged over the temperature range  $-109.7$  to  $440.3^{\circ}$ F. For the case  $E < E_o$  (the two-phase branch), the explicit dependence of  $E$  on  $M_a$ ,  $M_s$ ,  $M_w$ , and  $T$  is

$$E = M_a c_{va} T + M_s(T) e_{sat}(T) + M_w(T) e_w(T) \quad (\text{Eq. 6B-8})$$

The functions  $e_s(P_s, T)$  and  $e_w(T)$  are the specific internal energies of steam and water respectively and are also discussed in Section 6B. 3. The steam and water masses are functions of temperature only and are given by

$$M_s(T) = x(T) M_v = \frac{V - M_v v_w(T)}{v_{sat}(T) - v_w(T)} \quad (\text{Eq. 6B-9})$$

and

$$M_w(T) = M_v - M_s(T) \quad (\text{Eq. 6B-9})$$

where the steam quality  $x(T)$  is defined by the following:

$$x(T) = \frac{M_s(T)}{M_v} = \frac{V/M_v - v_w(T)}{v_{sat}(T) - v_w(T)} \quad (\text{Eq. 6B-10})$$

For the case  $E > E_o$  (the superheat branch), the explicit dependence of  $E$  is given by

$$E = M_a c_{va} T + M_s e_s(P_s, T) \quad (\text{Eq. 6B-11})$$

The steam mass  $M_s$  is not a function of temperature since it is equal to the vapor mass  $M_v$ , and of course the water mass is zero.

Because  $E$  is a complex function of  $T$  as seen by the above, EQ. 6B-5 does not readily lend itself to a strictly analytical solution. Instead, FLUD employs a one-pass iterative technique to solve for the temperature.

### 6B.1.3 Compartment Initial Conditions

The initial thermodynamic state is specified for each compartment by the total compartment pressure  $P$ , and the compartment volume  $V$ , temperature  $T$ , relative humidity  $\phi$ , and vapor quality  $x$ .

If  $\phi < 1.0$ , the compartment is superheated, the vapor consists entirely of steam, and the steam mass is given by definition as

$$M_s = \phi \frac{V}{v_{sat}(T)} \quad (\text{Eq. 6B-12})$$

The steam partial pressure is obtained from Eq. 6B-4, and thus the air mass is given by Eq. 6B-3. The internal energy is calculated using Eq. 6B-11. If  $\phi = 1.0$  and  $x = 1.0$ , the compartment is saturated. The steam partial pressure is given by the saturation pressure  $P_s = P_{sat}(T)$ . The saturation pressure of steam  $P_{sat}$  is obtained empirically from a curve fit to the steam tables. The steam mass is given by Eq. 6B-12 with  $\phi = 1.0$ . The vapor mass is identically equal to the steam mass, and the internal energy is computed from Eq. 6B-7. For  $\phi = 1.0$  and  $x < 1.0$ , the compartment is two-phase. The vapor and steam masses are given by Eq. 6B-9 and the water mass by Eq. 6B-9. The steam partial pressure is equal to the saturation pressure  $P = P_{sat}(T)$ . Therefore, the air mass can be calculated from Eq. 6B-3. However, because the compartment now contains water, the volume accessible to the air and steam  $V_g$  is just

$$V_g = V - M_w v_{sat}(T) \quad (\text{Eq. 6B-13})$$

This gas volume  $V_g$  must be used in place of  $V$  in Eq. 6B-3 in determining the air mass. The internal energy is obtained from Eq. 6B-8.

### 6B.1.4 Air and Vapor Component Flow Rates

The time-dependent partial pressure of steam is given by Eq. 6B-4 where  $v_s$  replace  $V/M_s$ . The time-dependent air specific volume  $v_a$  is then obtained from Eq. 6B-3. Time-dependent air and steam mass fractions are then calculated as follows:

$$f_a = v_s(v_s + v_a)^{-1} \quad (\text{Eq. 6B-14})$$

$$f_v = v_a(v_s + v_a)^{-1} \quad (\text{Eq. 6B-14})$$

The flow rates of the air and vapor components that comprise the gas are calculated from the total flow rate  $\dot{M}_{ij}$  by using the mass fractions of air and vapor in the upstream compartment:

$$\dot{M}_{air} = f_a \dot{M}_{ij} \quad (\text{Eq. 6B - 15})$$

$$\dot{M}_{vij} = f_v \dot{M}_{ij} \quad (\text{Eq. 6B - 16})$$

## 6B.2 Energy Transfer Mechanisms

There are several mechanisms by which FLUD transfers energy to and from the various compartments and the atmosphere. These mechanisms are:

- (1) Blowdown energy
- (2) Flow of energy between compartments
- (3) Compartment heat loads
- (4) Compartment unit coolers

All of these mechanisms add or subtract energy from the system. A continuous accounting of all energy contributors is kept by FLUD in the form of an overall energy balance to ensure energy conservation. The various energy transfer mechanisms are discussed and the energy balance are discussed below.

### 6B.2.1 Blowdown Energy

Blowdown energy is added to the system of compartments when FLUD is used to analyze a high-energy pipe break problem. The blowdown flow rate  $\dot{M}_B$ , specific enthalpy  $h_B$ , and the split among compartments are assumed to be given as input data. The rate of energy addition to the system by blowdown  $\dot{H}_B$  is usually a time-varying quantity given by

$$\dot{H}_B = \dot{M}_B h_B \quad (\text{Eq. 6B - 17})$$

This variable energy rate is used to calculate the amount of energy that is placed in one or in the various break compartments during each time step. The total amount of blowdown energy added to the system is the integral of  $\dot{H}_B$ .

$$\dot{H}_B(t) = \int_0^t \dot{H}_B dt \quad (\text{Eq. 6B - 18})$$

The blowdown energy rate added to the  $i$ th compartment is calculated by multiplying the user-supplied split fraction for the  $i$ th compartment times the total blowdown energy rate in Eq. 6B-17.

### 6B.2.2 Enthalpy Flow

Whenever mass is transferred between compartments or between a compartment and the atmosphere, there is an associated transfer of energy based upon the enthalpy of the upstream compartment. The general relation used to calculate enthalpy flow between compartments is

$$\dot{H}_i = \sum_j \dot{M}_{ij} h_{ij}^* \quad (\text{Eq. 6B - 19})$$

where  $h_{ij}^*$  represents the total specific enthalpy of the gas in the upstream compartment and  $\dot{M}_{ij}$  is the flow rate between compartments  $i$  and  $j$  as discussed in 6B.1.4. The total enthalpy flow rate for the system is

$$\dot{H} = \sum_i \dot{H}_i \quad (\text{Eq. 6B - 20})$$

When energy transfer occurs between a compartment and the atmosphere, the relation used to calculate this flow is

$$\dot{H}_{atm,i} = \dot{M}_{ii} h_{ii}^* \quad (\text{Eq. 6B - 21})$$

Here  $\dot{M}_{ii}$  represents the total flow from or to the atmosphere from component  $i$  and  $h_{ii}^*$  is the specific enthalpy of the upstream compartment (which may be either compartment  $i$  or the atmosphere depending upon the sign of  $\dot{M}_{ii}$ ). The total enthalpy flow rate to the atmosphere is

$$\dot{H}_{atm} = \sum_i \dot{H}_{atm,i} \quad (\text{Eq. 6B - 22})$$

and the total amount of energy transferred to the atmosphere is

$$H_{atm}(t) = \int_0^t \dot{H}_{atm} dt \quad (\text{Eq. 6B - 23})$$

### 6B.2.3 Compartment Heat Loads

Heat is generated within a compartment in the case where pumps or equipment are operating in that compartment. These heat loads are given with the input data as a

constant heat rate (Btu/sec) for each compartment  $\dot{Q}_{load}$ . These heat loads are assumed to be applicable throughout the problem under consideration.

#### 6B.2.4 Unit Coolers

Unit coolers or room coolers are present in many situations, especially in compartments that have equipment capable of generating large heat loads. Room coolers can have a variable start temperature which is specified in the input data. The coolers are usually set to begin operating when the compartment temperature exceeds some prescribed limit.

The cooling heat transfer rate is given by

$$\dot{Q}_{cool} = \alpha(T - T_{cool}) \quad (\text{Eq. 6B-24})$$

where  $T_{cool}$  is the cooler cold water inlet temperature,  $T$  is the temperature of the compartment, and  $\alpha$  is the cooler constant (Btu/sec-°R). The cooler constant can be calculated from room cooler specifications and is assumed to be constant throughout the temperature ranges of the room atmosphere and the cooling water temperature.

#### 6B.2.5 Energy Balance

The energy balance given by the following equations is used to ensure that energy conservation is achieved.

$$E_{bal} = E_i + \dot{Q}dt + \dot{H}_{atm}dt - \dot{H}_Bdt - E_i(0) \quad (\text{Eq. 6B-25})$$

where  $E_i$  is the total energy in the  $i$ th compartment,  $E_i(0)$  is the initial compartment energy, and

$$\dot{Q} = \dot{Q}_c + \dot{Q}_{load} + \dot{Q}_{cool} \quad (\text{Eq. 6B-26})$$

If an energy balance is achieved, then  $E_{bal}$  should be zero.

#### 6B.2.6 Blowout Panel Activation

Blowout panels are treated as instantaneous one-way switches. Once a blowout panel set pressure is exceeded, the flowpath is open for the duration of the calculation. The actual activation of a blowout panel is made by setting the forward and reverse set pressures equal to zero once the forward set pressure has been exceeded.

6B.2.7 Energy and Mass Conservation

Energy and mass conservation is then checked by calculating the following quantities:

$$E_{bal} = \sum E_i + \int \dot{Q} dt + \int \dot{H}_{atm} dt - \int \dot{H}_B dt - E_{init} \quad (\text{Eq. 6B - 27})$$

and

$$M_{bal} = \sum M_i + \int \dot{M}_o dt + \int \dot{M}_{atm} dt - \int \dot{M}_B dt - M_{init} \quad (\text{Eq. 6B - 28})$$

If all mass and energy transfer has been accounted for, then  $E_{bal}$  and  $M_{bal}$  should be zero (or a very small percentage of the total energy and mass due to computer round-off error).

6B.2.8 Eulerian Integration

The time-dependent quantities listed below are integrated according to the following general scheme:

$$X(T + \Delta t) = X(t) + \dot{X}(t)\Delta t \quad (\text{Eq. 6B - 29})$$

where  $X$  is any time dependent variable and  $\dot{X}$  is its time rate of change. The variables integrated by FLUD are:

- $\dot{H}_B$  - blowdown enthalpy flow rate
- $\dot{M}_B$  - blowdown mass flow rate
- $\dot{E}$  - energy rate of change
- $\dot{H}_{atm}$  - atmospheric enthalpy flow rate
- $\dot{M}_a$  - air mass flow rate
- $\dot{M}_v$  - vapor mass flow rate
- $\dot{M}_{atm}$  - atmospheric mass flow rate

6B.3 Thermodynamic Properties of Steam, Water, and Air

FLUD uses steam, air, and water properties for various thermodynamic calculations which are performed during each time step. The thermodynamic variables needed in FLUD calculations are:

$e_a(T)$	specific internal energy of air
$P_{sat}(T)$	saturation pressure of steam
$v_{sat}(T)$	saturation specific volume of steam
$e_s(T,P)$	specific internal energy of steam
$v_w(T)$	specific volume of water
$e_w(T)$	specific internal energy of water
$T_{sat}(P)$	saturation temperature of steam
$T_{sat}(v)$	saturation temperature of steam
$e_{sat}(T)$	saturation specific internal energy of steam
$h_{sat}(T)$	saturation specific enthalpy of steam
$h_{fg}(P)$	enthalpy of vaporization of steam

The "known" quantities that can be used to calculate the above nine variables are the macroscopic compartment thermodynamic variables pressure, specific volume, and temperature,  $P$ ,  $v$ , and  $T$  respectively.

The air and water properties  $e_a(T)$ ,  $v_w(T)$ , and  $e_w(T)$  are calculated by spline fitting polynomials to data in the steam and gas tables<sup>2, 3</sup>. The air property  $e_a(T)$  was found to be adequately represented by a linear fit. This is no doubt due to the good "ideal gas" behavior of air. Thus,

$$e_a(T) = a_1 T \quad (\text{Eq. 6B-30})$$

The water properties  $v_w(T)$  and  $e_w(T)$  and the steam properties  $h_{sat}(T)$ ,  $e_o(T)$ , and  $e_{sat}(T)$  are very nearly straight line functions, but small variations were accommodated by using third order spline polynomial fits of the general form:

$$\text{property}(T) = a_0 + a_1 T + a_2 T^2 + a_3 T^3 \quad (\text{Eq. 6B-31})$$

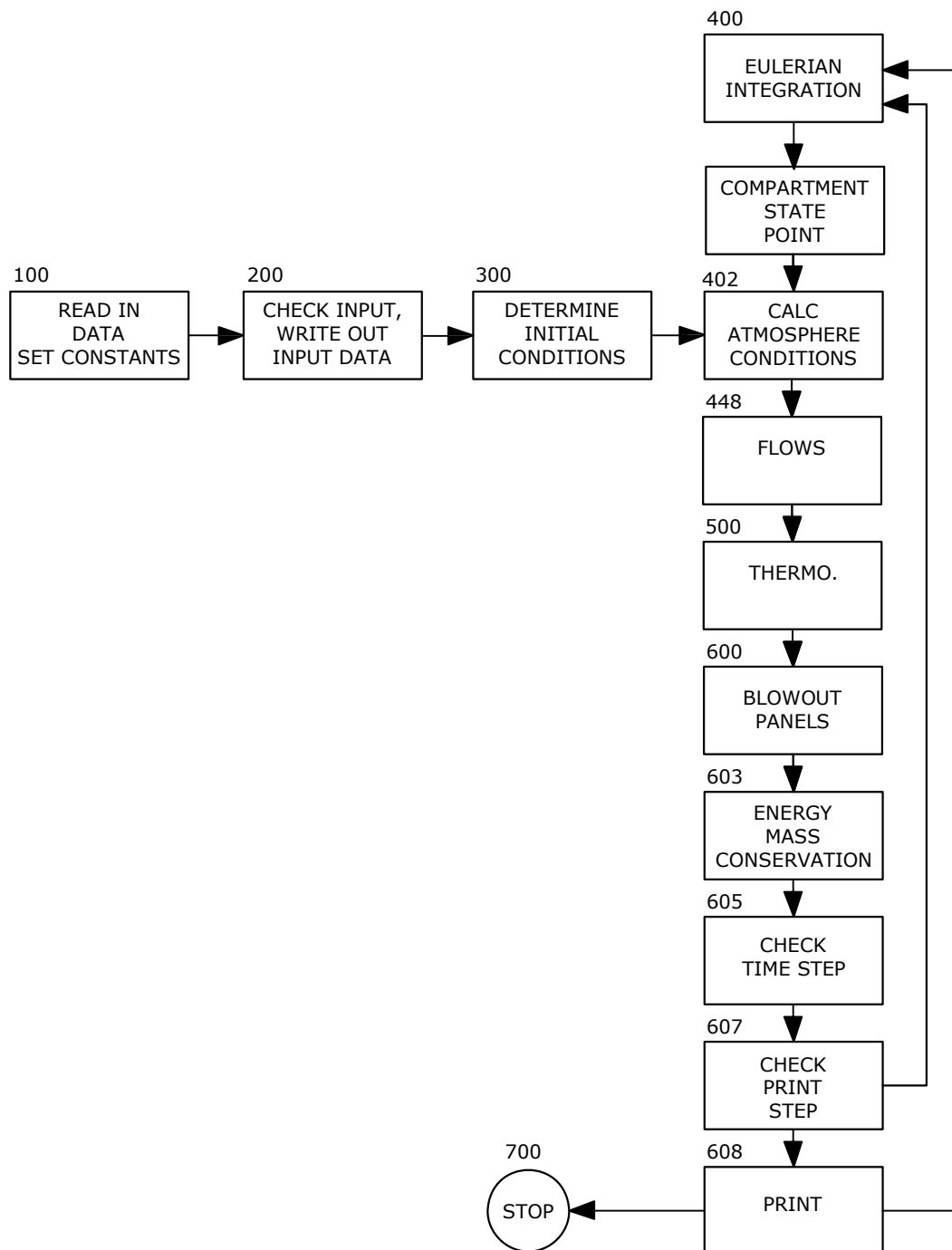
For example, for  $h_{fg}(P)$ ,

$$h_{fg}(P) = a_0 + a_1P + a_2P^2 + a_3P^3 \quad (\text{Eq. 6B-32})$$

The accuracy of the curve fits the range between 0.01% and 4%<sup>3</sup> for the various properties.

#### 6B.4 References

- 6B-1 Reif, F. J. Fundamentals of Statistical and Thermal Physics, McGraw-Hill Book Co., p. 183.
- 6B-2 Kennan, J. H. et al, Steam Tables, John Wiley & Sons, Inc., New York, 1969.
- 6B-3 Kennan, J. H., and J. Kaye, Gas Tables, John Wiley & Sons, Inc., New York, 1948.
- 6B-4 Bechtel Topical Report BN-TOP-4 Rev. 1, October 1977, "Subcompartment Pressure and Temperature Transient Analysis." This report was approved by the NRC in February, 1979.



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FINAL SAFETY ANALYSIS REPORT

BASICE FLUD CALCULATION  
FLOWCHART

FIGURE 6B-1, Rev. 47

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