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ATTENTION: T. R. QUAY

SUBJECT: AP600 PCS SCALING, PRESSURE CHANGE EQUATION

Dear Mr. Quay:

The enclosure to this letter provides the development of the rate of pressure change equation for scaling the AP600 containment. This equation development is being incorporated into the revision of the PCS scaling report and is provided at this time to facilitate ongoing NRC review activities. A draft of this material was discussed during the April 22-23, 1996 meeting between Westinghouse and NRC staff.

Please contact John C. Butler on (412) 374-5268 if you have any questions concerning this transmittal.

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## RPC EQUATION GOAL AND ASSUMPTIONS

The goal for this part of the scaling analysis is to develop an equation that represents the containment gas rate of pressure change (RPC) due to the sources and heat and mass transfer to the containment shell and internal heat sinks (steel, concrete, rain, fog, and pools), and to couple the RPC equation to the shell and heat sinks by thermal resistances. The equation should be in a form that minimizes unknowns.

Assumptions for the development of the equations are:

The mass of the gas mixture is the sum of the individual air and steam masses:  $m = m_{air} + m_{stm}$ .

The internal energy of the mixture,  $U$ , is the sum of the individual air and steam internal energies, that is, there is no reaction between the two:  $U = mu = m_{air}u_{air} + m_{stm}u_{stm}$ .

The Dalton rule for additive partial pressures: the total pressure is the sum of the air and steam partial pressures,  $P = P_{air} + P_{stm}$ .

Air can be approximated as an ideal gas due to high reduced temperature and low reduced pressure ( $T_r > 2$  and  $P_r < 0.05$ ). Thus  $P_{air}V = Z_{air}m_{air}R_{air}T$  where the compressibility factor  $Z_{air} = 1$ .

Steam is a real gas with equation of state  $P_{stm}V = Z_{stm}m_{stm}R_{stm}T$  where the compressibility factor  $Z_{stm} = Z_{stm}(P_{stm}, T)$ . Steam properties are from steam tables.

There is no liquid-vapor phase change within the gas control volume. Phase change occurs after the gas passes out of the gas control volume.

The RPC equation is developed from the equations of state, conservation of mass, and conservation

of energy for a control volume. Extensive properties are defined in terms of the gas mixture  $P$ ,  $T$ ,  $m_{\text{air}}$ , and  $m_{\text{stm}}$ . Intensive properties are defined in terms of  $P$ ,  $T$ , and the steam mass concentration,  $C$ . In the development of the RPC, the equation of state is used to eliminate the variable  $T$ , and the derivative of the equation of state is used to eliminate the variable  $dT$  from the final expression. The gas mixture relationships are defined, and the energy transfer resistances are derived.

## Mixture Properties

### Mass

On a mass basis the mass of mixture is the sum of the masses of the individual gasses:

$$m = m_{\text{air}} + m_{\text{stm}} \quad (1)$$

On a molar basis for a non-reacting mixture, the number of moles of gas mixture is the sum of the moles of individual gasses:

$$n = n_{\text{air}} + n_{\text{stm}} \quad (2)$$

### Molecular Weight

Because the number of moles is defined  $n = m/M$ , the mixture molecular weight can be defined from (2):

$$\frac{m}{M} = \frac{m_{\text{air}}}{M_{\text{air}}} + \frac{m_{\text{stm}}}{M_{\text{stm}}} \quad \text{so} \quad M = \frac{m_{\text{air}} + m_{\text{stm}}}{m_{\text{air}}/M_{\text{air}} + m_{\text{stm}}/M_{\text{stm}}} \quad (3)$$

### Gas Constant

The mixture gas constant can be determined from (3) and the definition of the gas constant  $R = \bar{R}/M$

$$R = \frac{\bar{R}(m_{\text{air}}/M_{\text{air}} + m_{\text{stm}}/M_{\text{stm}})}{(m_{\text{air}} + m_{\text{stm}})} \quad \text{so} \quad R = \frac{m_{\text{air}}R_{\text{air}} + m_{\text{stm}}R_{\text{stm}}}{m} \quad (4)$$

Defining the steam concentration  $C = m_{\text{stm}}/m$ , the air concentration is  $(1-C)$ , so Equation (4) can be written:

$$R = (1 - C)R_{\text{air}} + CR_{\text{stm}} \quad (5)$$

### Enthalpy

The mixture enthalpy can be derived from the definition of enthalpy,  $H = mh = mu + PV$ , the internal energy of the mixture,  $mu = m_{\text{air}}u_{\text{air}} + m_{\text{stm}}u_{\text{stm}}$ , and the Dalton rule,  $P = P_{\text{air}} + P_{\text{stm}}$ :

$$\begin{aligned} mh &= m_{\text{air}}u_{\text{air}} + m_{\text{stm}}u_{\text{stm}} + P_{\text{air}}V + P_{\text{stm}}V \\ \text{so } h &= \frac{m_{\text{air}}h_{\text{air}} + m_{\text{stm}}h_{\text{stm}}}{m} \quad \text{or} \quad h = (1 - C)h_{\text{air}} + Ch_{\text{stm}} \end{aligned} \quad (6)$$

### Specific Heat

The mixture constant pressure specific heat can be derived by taking the partial derivative of  $mh$  with respect to temperature, and noting that the masses are not functions of temperature:

$$\begin{aligned} \frac{\partial}{\partial T}(mh) &= \frac{\partial}{\partial T}(m_{\text{air}}h_{\text{air}} + m_{\text{stm}}h_{\text{stm}}) \quad \text{so} \quad m \frac{\partial h}{\partial T} = m_{\text{air}} \frac{\partial h_{\text{air}}}{\partial T} + m_{\text{stm}} \frac{\partial h_{\text{stm}}}{\partial T} \\ \text{and } c_p &= \frac{m_{\text{air}}c_{p,\text{air}} + m_{\text{stm}}c_{p,\text{stm}}}{m} \quad \text{or} \quad c_p = (1 - C)c_{p,\text{air}} + Cc_{p,\text{stm}} \end{aligned} \quad (7)$$

A similar approach can be applied to the internal energy to derive the mixture constant volume specific heat:

$$c_v = \frac{m_{\text{air}}c_{v,\text{air}} + m_{\text{stm}}c_{v,\text{stm}}}{m} \quad \text{or} \quad c_v = (1 - C)c_{v,\text{air}} + Cc_{v,\text{stm}} \quad (8)$$

### Gas Compressibility

The gas mixture compressibility,  $Z$ , can be derived from the Dalton rule and the equation of state:

$$P = P_{air} + P_{stm} \quad \text{and} \quad P = \frac{Zn\bar{R}T}{V} \quad \text{so} \quad Zn\frac{\bar{R}T}{V} = (Zn)_{air}\frac{\bar{R}T}{V} + (Zn)_{stm}\frac{\bar{R}T}{V} \quad (9)$$

Deleting  $\bar{R}T/V$  from each term and divide by  $n$ :

$$Z = \frac{n_{air}Z_{air} + n_{stm}Z_{stm}}{n} \quad (10)$$

With  $n\bar{R} = mR$ , Equation (10) can be written:

$$ZmR = Z_{air}m_{air}R_{air} + Z_{stm}m_{stm}R_{stm} \quad \text{or} \quad ZR = (1-C)Z_{air}R_{air} + CZ_{stm}R_{stm} \quad (11)$$

The derivative of  $ZR$  is:

$$d(ZR) = -Z_{air}R_{air}dC + (1-C)(Z_{air}dR_{air} + R_{air}dZ_{air}) + Z_{stm}R_{stm}dC + C(Z_{stm}dR_{stm} + R_{stm}dZ_{stm}) \quad (12)$$

The values of  $Z_{air}$ ,  $R_{air}$ , and  $R_{stm}$  are constants, so Equation (12) can be simplified to:

$$d(ZR) = dC(Z_{stm}R_{stm} - Z_{air}R_{air}) + CR_{stm}dZ_{stm} \quad (13)$$

Whereas the concentration,  $C$ , can range from 0 to 1,  $Z_{stm}$  is limited to the range 0.97 to 1.0. Therefore, the derivative  $dZ_{stm}$  can be neglected and  $dZR$  expressed:

$$d(ZR) = dC(Z_{stm}R_{stm} - Z_{air}R_{air}) \quad (14)$$

The property  $Z^T$ , where  $Z^T = (T/Z)\partial Z / \partial T$ , can be expressed in terms of  $Z_{air}^T$  and  $Z_{stm}^T$  with Equation (10):

$$\frac{T}{Z} \frac{\partial Z}{\partial T} = \frac{T}{Z} \frac{\partial \left( \frac{n_{air}}{n} Z_{air} + \frac{n_{stm}}{n} Z_{stm} \right)}{\partial T} = \frac{T}{Z} \frac{n_{stm}}{n} \frac{\partial Z_{stm}}{\partial T} \quad (15)$$

since  $n$ ,  $n_{air}$ ,  $n_{stm}$ , and  $Z_{air}$  are not functions of temperature. With the substitution  $Z_{stm} n_{stm} / Zn = P_{stm} / P$ :

$$\frac{T}{Z} \frac{n_{stm}}{n} \frac{\partial Z_{stm}}{\partial T} = \frac{Z_{stm}}{Z} \frac{n_{stm}}{n} \frac{T}{Z_{stm}} \frac{\partial Z_{stm}}{\partial T} = \frac{P_{stm}}{P} Z_{stm}^T = Z^T \quad (16)$$

For steam at 40 psi and 280 °F the magnitude of  $Z_{stm}^T$  is 0.13. Consequently, the temperature derivative of the compressibility factor may be significant.



## Mixture Enthalpy

The gas mixture total enthalpy,  $H = mh = m_{\text{air}}h_{\text{air}} + m_{\text{stm}}h_{\text{stm}}$  is a function of the four independent variables  $P, T, m_{\text{air}}, m_{\text{stm}}$ . The derivative of  $H$  can be written:

$$d(mh) = m \frac{\partial h}{\partial T} dT + m \frac{\partial h}{\partial P} dP + h_{\text{air}} \frac{\partial m_{\text{air}}}{\partial m_{\text{air}}} dm_{\text{air}} + h_{\text{stm}} \frac{\partial m_{\text{stm}}}{\partial m_{\text{stm}}} dm_{\text{stm}} \quad (17)$$

$$\text{so } d(mh) = mc_p dT + m \frac{\partial h}{\partial P} dP + h_{\text{air}} dm_{\text{air}} + m_{\text{stm}} dm_{\text{stm}}$$

Examination of the steam tables shows that along the saturation line from 38 to 42 psia,  $\Delta h = 1.9$  B/lbm, while  $c_p \Delta T = 3.0$  B/lbm and  $(\partial h / \partial P) \Delta P = -1.1$  B/lbm. Although containment pressurization does not follow the saturation line exactly, it does follow with at most a modest superheat. Consequently, the rate of change of enthalpy due to pressure is approximately -1/2 of the total, while that due to temperature is 3/2 of the total. Clearly, pressure may be a substantial contributor to enthalpy, and thus to pressure. The presence of air inside containment will reduce the contribution of pressure to system enthalpy somewhat.

From thermodynamic relationships, the partial derivative of enthalpy with respect to pressure can be written in terms of a temperature derivative:

$$\frac{\partial h}{\partial P} = v - T \frac{\partial v}{\partial T} \quad (18)$$

With the equation of state  $v = ZRT/P$ , and considering  $Z$  and  $v$  to be functions of the independent variables  $P, T$ , and  $C$ , the pressure derivative of enthalpy is:

$$\frac{\partial h}{\partial P} = v - T \left( \frac{RT}{P} \frac{\partial Z}{\partial T} + \frac{ZR}{P} \right) \quad \text{so} \quad \frac{\partial h}{\partial P} = -T \frac{v}{Z} \frac{\partial Z}{\partial T} \quad (19)$$

With this expression and the abbreviation  $Z^T = (T/Z)(\partial Z / \partial T)$ ,  $dmh$  can also be written:

$$d(mh) = mc_p dT - v Z^T dP + h_{\text{air}} dm_{\text{air}} + h_{\text{stm}} dm_{\text{stm}} \quad (20)$$



### Specific Heats

From the definition of the constant pressure and constant volume specific heats, and the definition of enthalpy:

$$c_p - c_v = \frac{\partial h}{\partial T} - \frac{\partial u}{\partial T} = \frac{\partial(u + Pv)}{\partial T} - \frac{\partial u}{\partial T} \quad \text{so} \quad c_p - c_v = \frac{\partial Pv}{\partial T} \quad (21)$$

Substituting the equation of state,  $Pv = ZRT$ :

$$c_p - c_v = \frac{\partial(ZRT)}{\partial T} = ZR \frac{\partial T}{\partial T} + RT \frac{\partial Z}{\partial T} \quad \text{so} \quad c_p - c_v = ZR(1 + \frac{T}{Z} \frac{\partial Z}{\partial T}) \quad (22)$$

With the substitution  $Z^T = (T/Z) \partial Z / \partial T$

$$c_p - c_v = ZR(1 + Z^T) \quad (23)$$

With the specific heat ratio  $\gamma = c_p/c_v$ , the ratio  $c_p/ZR$  can be expressed:

$$\frac{c_p}{ZR} = \frac{\gamma}{(\gamma - 1)}(1 + Z^T) \quad (24)$$

### Equation of State

Starting with the equation of state,  $T = PV/ZmR$ , and differentiating:

$$dT = T \left( \frac{d(PV)}{PV} - \frac{d(ZR)}{ZR} - \frac{dm}{m} \right) \quad (25)$$

Substituting Equation (14) for  $d(ZR)$ :

$$dT = T \left[ \frac{d(PV)}{PV} - \frac{(Z_{stm} R_{stm} - Z_{air} R_{air})dC}{ZR} - \frac{dm}{m} \right] \quad (26)$$

Or, in terms of the individual air and steam masses:

$$dT = T \left[ \frac{d(PV)}{PV} - \frac{Z_{air} R_{air} dm_{air}}{ZR} - \frac{Z_{stm} R_{stm} dm_{stm}}{ZR} \right] \quad (27)$$

# RATE OF CHANGE OF INTERNAL ENERGY

The total derivative of the gas mixture internal energy can be expressed in terms of enthalpy and pressure:

$$d(\mu) = d(mh - PV) = d(mh) - d(PV) \quad (28)$$

Substituting Equation (20) for dmh:

$$d(\mu) = m c_p dT - V Z^T dP + h_{air} dm_{air} + h_{stm} dm_{stm} - d(PV) \quad (29)$$

Now substitute Equation (26) for dT:

$$d(\mu) = m c_p T \left[ d(PV) \frac{1}{PV} - \frac{(Z_{stm} R_{stm} - Z_{air} R_{air}) dC}{ZR} - \frac{dm}{m} \right] - V Z^T dP + h_{air} dm_{air} + h_{stm} dm_{stm} - d(PV) \quad (30)$$

Substitute PV/ZR for mT and combine coefficients on dPV:

$$d(\mu) = \left( \frac{c_p}{ZR} - 1 \right) d(PV) - \frac{c_p PV}{ZR} \left[ \frac{(Z_{stm} R_{stm} - Z_{air} R_{air}) dC}{ZR} + \frac{dm}{m} \right] - V Z^T dP + h_{air} dm_{air} + h_{stm} dm_{stm} \quad (31)$$

Substitute Equation (24) for  $c_p/ZR$  and combine dP terms:

$$d(\mu) = \frac{(1+Z^T)}{(\gamma-1)} V dP + \frac{(1+\gamma Z^T)}{(\gamma-1)} P dV - \frac{\gamma(1+Z^T)}{(\gamma-1)} P V \frac{(Z_{stm} R_{stm} - Z_{air} R_{air})}{ZR} dC$$

$$- \frac{\gamma(1+Z^T)}{(\gamma-1)} P V \frac{dm}{m} + h_{air} dm_{air} + h_{stm} dm_{stm}$$
(32)

Or in terms of air and steam mass, instead of total mass and concentration:

$$d(\mu) = \frac{(1+Z^T)}{(\gamma-1)} V dP + \frac{(1+\gamma Z^T)}{(\gamma-1)} P dV - \frac{\gamma(1+Z^T)}{(\gamma-1)} P V \frac{Z_{air} R_{air}}{ZR} dm_{air}$$

$$- \frac{\gamma(1+Z^T)}{(\gamma-1)} P V \frac{Z_{stm} R_{stm}}{ZR} dm_{stm} + h_{air} dm_{air} + h_{stm} dm_{stm}$$
(33)

## CONSERVATION OF MASS AND ENERGY

The conservation equations are written for a gas control volume with multiple steam sources and sinks, and with multiple convective inflows and outflows.

### Conserve Mass

Conservation of mass applied to a control volume can be stated as "the rate of change of mass in a control volume is equal to the sum of the mass fluxes in and out of the control volume". The equation for conservation of mass for a control volume encompassing only the containment gas can be written:

$$\frac{dm}{dt} = \dot{m}_{brk} + \sum (\dot{m}_{air,i} + \dot{m}_{stm,i}) + \sum \dot{m}_{stm,j} \quad (34)$$

where the index  $i$  represents convective air and steam terms, and  $j$  represents condensation or evaporation steam mass transfer terms. Positive flows are into the control volume and negative flows are out. Conservation of mass can also be applied to each gas species (air and steam) with the result:

$$\frac{dm_{air}}{dt} = \sum \dot{m}_{air,i} \quad \text{and} \quad \frac{dm_{stm}}{dt} = \dot{m}_{brk} + \sum \dot{m}_{stm,i} + \sum \dot{m}_{stm,j} \quad (35)$$

Conservation of mass can also be applied to the liquid that forms part of the gas control volume. The total liquid mass includes the masses of the IRWST, break pool, drops, and liquid films. These are the liquid masses that displace gas in the containment volume, and cause the containment pressure to change.

The liquid mass conservation equation is:

$$\frac{dm_l}{dt} = \dot{m}_{brk,l} - \dot{m}_{IRWST} - \sum \dot{m}_{stm,j} \quad (36)$$

The break liquid includes the drops, as well as the liquid that pours into the break pool. The term  $\dot{m}_{stm,j}$  =  $-\dot{m}_{t,j}$ , that is, the mass of gas that changes phase (either condensed from or evaporated to) the atmosphere is equal in magnitude, but opposite in sign to the mass of liquid that changes phase. The IRWST flow drains into the reactor (hence the minus sign) and subsequently is released from the break as liquid and/or steam. The liquid and steam from the primary cooling system (piping, pumps, steam generators, accumulators, and pressurizer) only appear as break source terms.

### Conserve Energy

Conservation of energy for a control volume can be stated as "the rate of change of internal energy in a control volume is equal to the sum of the enthalpy fluxes and the heat transfer in and out of the control volume. Conservation of energy for the control volume encompassing only the containment gas can be written:

$$\frac{d(mu)}{dt} = \dot{m}_{brk} h_{brk} + \sum (\dot{m}_{air,i} h_{air,i} + \dot{m}_{stm,i} h_{stm,i}) + \sum (\dot{m}_{stm,j} h_{stm,j} + h A_j (T_j - T)) \quad (37)$$

where  $h_{brk}$  is the total break steam enthalpy,  $h_{brk} = h + v^2/2 + gz$ . Elevation is negligible, as is  $v^2/2$  for all but the break source during blowdown. (Post-blowdown,  $v < 200$  ft/sec, so  $v^2/2 < 0.8$  BTU/lbm). The evaporation and condensation rates in containment pressurization are never high enough to have to consider total enthalpy. With Equations (1), (6), (28), and (35), the energy equation can be written:

$$m \frac{du}{dt} = \dot{m}_{brk} (h_{brk} - h) + \sum \dot{m}_i (h_i - h) + \sum (\dot{m}_{stm,j} (h_{stm,j} - h) + h A_j (T_j - T)) + \frac{P}{\rho} \frac{dm}{dt} \quad (38)$$



## RATE OF PRESSURE CHANGE EQUATION

A rate of pressure change equation can be written by combining the equation for the rate of change of internal energy, Equation (32) can be combined with the conservation of energy equation, Equation (37), and rearranged in terms of the pressure derivative:

$$\frac{(1+Z^T)}{(\gamma-1)} V \frac{dP}{dt} = \dot{m}_{brk} h_{brk} + \sum (\dot{m}_{air,i} h_{air,i} + \dot{m}_{stm,i} h_{stm,i}) + \sum (\dot{m}_{stm,j} h_{stm,j} + h_j A_j (T_j - T)) - h_{air} \frac{dm_{air}}{dt} - h_{stm} \frac{dm_{stm}}{dt} + \frac{\gamma(1+\gamma Z^T)}{(\gamma-1)} P V \frac{(Z_{stm} R_{stm} - Z_{air} R_{air})}{ZR} \frac{dC}{dt} + \frac{\gamma(1+\gamma Z^T)}{(\gamma-1)} P V \frac{dm}{dt} - \frac{(1+\gamma Z^T)}{(\gamma-1)} P \frac{dV}{dt} \quad (39)$$

The  $dm_{air}/dt$  and  $dm_{stm}/dt$  terms in Equation (39) can be replaced by Equation (35), giving:

$$\frac{(1+Z^T)}{(\gamma-1)} V \frac{dP}{dt} = \dot{m}_{brk} (h_{brk} - h_{stm}) + \sum [\dot{m}_{air,i} (h_{air,i} - h_{air}) + \dot{m}_{stm,i} (h_{stm,i} - h_{stm})] + \sum [\dot{m}_{stm,j} (h_{stm,j} - h_{stm}) + h_j A_j (T_j - T)] + \frac{PV}{m} \frac{\gamma(1+Z^T)}{(\gamma-1)} \frac{dm}{dt} + \frac{\gamma(1+Z^T)}{(\gamma-1)} P V \frac{(Z_{stm} R_{stm} - Z_{air} R_{air})}{(ZR)} \frac{dC}{dt} - \frac{(1+\gamma Z^T)}{(\gamma-1)} P \frac{dV}{dt} \quad (40)$$

The first term on the right side of the equation represents the enthalpy flow rate of break steam. The second term, the summation over  $i$ , consists of two parts that represent the enthalpy flow rates of air and of steam convected in and out of the control volume, such as, through openings between compartments. Wherever there is an opening, both air and steam are expected to flow simultaneously. The third term, the summation over  $j$ , also consists of two parts. One part is mass transfer (condensation or evaporation) and the other part is convective heat transfer between the atmosphere and the shell, steel, concrete, drops, or pools. The fourth term ( $dm/dt$ ) is the work done on the gas by mass addition. The fifth term ( $dC/dt$ ) is the work done on the gas by the changing concentration. The sixth term is the work done on the gas by volume change: the displacement of gas by liquid in the fixed containment volume.

The pressure equation shows pressure increases when:

The enthalpy of influx source  $i$  is greater than the enthalpy of the gas already in the volume.

The enthalpy influx from surface  $j$  is greater than  $h$ , or  $T_{\text{surf}}$  is greater than  $T$ .

The net mass flux is  $> 0$ .

The steam concentration increases ( the coefficient on  $dC/dt$  is  $> 0$  since  $R_{\text{stm}}$  is nearly twice  $R_{\text{air}}$ ).

The gas volume decreases.

Alternatively, the energy equation can be combined with Equation (33) to give:

$$\begin{aligned} \frac{(1+Z^T)}{(\gamma-1)} V \frac{dP}{dt} = & \dot{m}_{\text{brk}} (h_{\text{brk}} - h_{\text{stm}}) + \sum [\dot{m}_{\text{air},i} (h_{\text{air},i} - h_{\text{air}}) + \dot{m}_{\text{stm},i} (h_{\text{stm},i} - h_{\text{stm}})] + \sum \dot{m}_{\text{stm},j} (h_{\text{stm},j} - h_{\text{stm}}) \\ & + \sum h A_i (T_i - T) + \frac{\gamma(1+Z^T)}{(\gamma-1)} \frac{P}{\rho} \frac{Z_{\text{air}} R_{\text{air}}}{ZR} \frac{dm_{\text{air}}}{dt} + \frac{\gamma(1+Z^T)}{(\gamma-1)} \frac{P}{\rho} \frac{Z_{\text{stm}} R_{\text{stm}}}{ZR} \frac{dm_{\text{stm}}}{dt} - \frac{(1+\gamma Z^T)}{(\gamma-1)} P \frac{dV}{dt} \end{aligned} \quad (41)$$

Substituting (35) for the time derivatives of air and steam mass gives:

$$\begin{aligned} \frac{(1+Z^T)}{(\gamma-1)} V \frac{dP}{dt} = & \dot{m}_{\text{brk}} \left[ h_{\text{brk}} - h_{\text{stm}} + \frac{\gamma(1+Z^T)}{(\gamma-1)} \frac{P}{\rho} \frac{Z_{\text{stm}} R_{\text{stm}}}{ZR} \right] \\ & + \sum \left[ \dot{m}_{\text{air},i} \left[ h_{\text{air},i} - h_{\text{air}} + \frac{\gamma(1+Z^T)}{(\gamma-1)} \frac{P}{\rho} \frac{Z_{\text{air}} R_{\text{air}}}{ZR} \right] + \dot{m}_{\text{stm},i} \left[ h_{\text{stm},i} - h_{\text{stm}} + \frac{\gamma(1+Z^T)}{(\gamma-1)} \frac{P}{\rho} \frac{Z_{\text{stm}} R_{\text{stm}}}{ZR} \right] \right] \\ & + \sum \left[ \dot{m}_{\text{stm},j} \left[ h_{\text{stm},j} - h_{\text{stm}} + \frac{\gamma(1+Z^T)}{(\gamma-1)} \frac{P}{\rho} \frac{Z_{\text{stm}} R_{\text{stm}}}{ZR} \right] + h A_j (T_j - T) \right] - \frac{(1+\gamma Z^T)}{(\gamma-1)} P \frac{dV}{dt} \end{aligned} \quad (42)$$

The only change in the containment gas volume is due to displacement by liquid water. The gas volume is the containment volume minus the liquid volume,  $V = V_{ct} - V_l$ , so  $dV/dT = -dV_l/dT$ . The liquid volume can be expressed as the liquid mass divided by the liquid density,  $V_l = m_l/\rho_l$ . It is sufficient to ignore the small liquid density variation with temperature. Consequently, with Equation (36), the volume rate of change term can be written:

$$-\frac{(1+\gamma Z^T)}{(\gamma-1)} P \frac{dV}{dt} = \frac{(1+\gamma Z^T)}{(\gamma-1)} \frac{P}{\rho_l} (\dot{m}_{brk,f} - \dot{m}_{IRWST} - \sum \dot{m}_{stm,j}) \quad (43)$$

With this equation, the RPC is expressed entirely in terms of mass flow rates and convective heat transfer. Each mass flow term carries enthalpy and does work on the gas volume. The work includes portions due to the change of gas mass, change of gas composition, and change of gas volume. The RPC is:

$$\begin{aligned} \frac{(1+Z^T)}{(\gamma-1)} V \frac{dP}{dt} = & \dot{m}_{brk} \left[ h_{brk} - h_{stm} + \frac{\gamma(1+Z^T)}{(\gamma-1)} \frac{P}{\rho} \frac{Z_{stm} R_{stm}}{ZR} \right] + \dot{m}_{brk,f} \frac{(1+\gamma Z^T)}{(\gamma-1)} \frac{P}{\rho_l} - \dot{m}_{IRWST} \frac{(1+\gamma Z^T)}{(\gamma-1)} \frac{P}{\rho_l} \\ & + \sum \left[ \dot{m}_{air,i} \left[ h_{air,i} - h_{air} + \frac{\gamma(1+Z^T)}{(\gamma-1)} \frac{P}{\rho} \frac{Z_{air} R_{air}}{ZR} \right] + \dot{m}_{stm,i} \left[ h_{stm,i} - h_{stm} + \frac{\gamma(1+Z^T)}{(\gamma-1)} \frac{P}{\rho} \frac{Z_{stm} R_{stm}}{ZR} \right] \right] \\ & + \sum \left[ \dot{m}_{stm,j} \left[ h_{stm,j} - h_{stm} + \frac{\gamma(1+Z^T)}{(\gamma-1)} \frac{P}{\rho} \frac{Z_{stm} R_{stm}}{ZR} - \frac{(1+\gamma Z^T)}{(\gamma-1)} \frac{P}{\rho_l} \right] + h A_j (T_j - T) \right] \end{aligned} \quad (44)$$

In this form, the rate of pressure change is expressed in terms of the containment gas properties, the temperature of the heat sinks, and the  $i$  and  $j$  subscripted mass flow rates. The break gas and liquid flow rates, and the IRWST liquid flow rate are known boundary conditions. The convective ( $i$  subscripted) flows can be calculated with a network momentum equation, or parametrically treated. The condensation and evaporation ( $j$  subscripted) mass flow rates can be calculated using a mass transfer conductance that couples the containment atmosphere to the heat sinks or to the PCS air flow path.