Chemical Engineering 612

Reactor Design and Analysis

Lecture 21

Nuclear Safety III

Accident Thermodynamics

Spiritual Thought

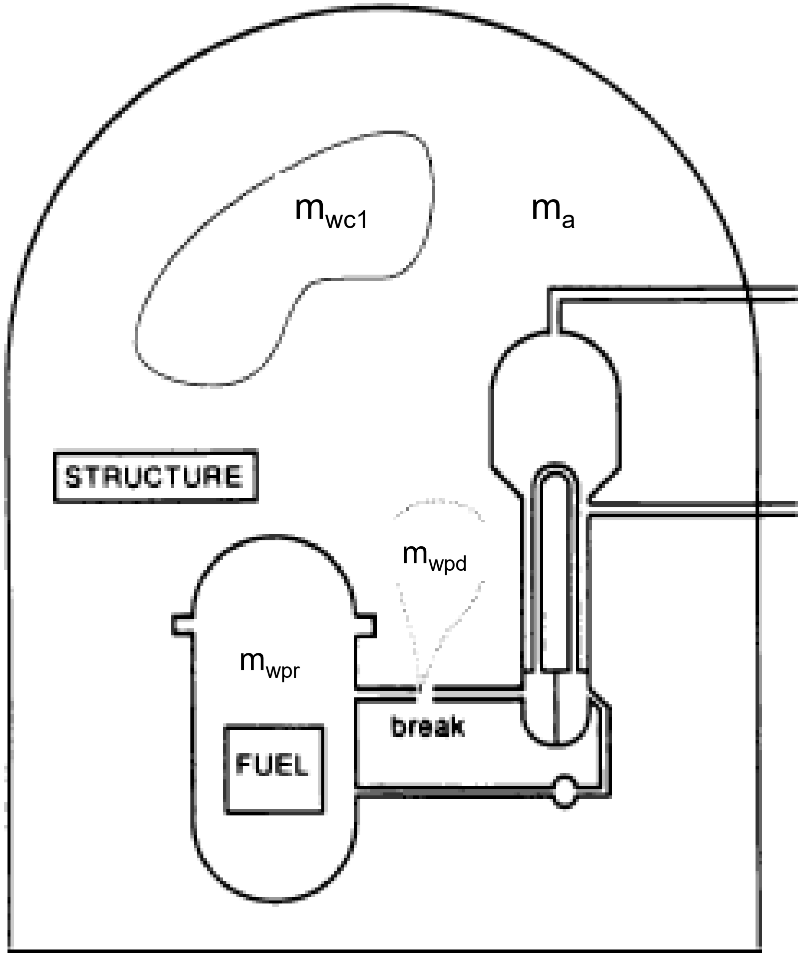
Ether 4:15

“Behold, when ye shall rend that veil of unbelief which doth cause you to remain in your awful state of wickedness, and hardness of heart, and blindness of mind, then shall the great and marvelous things which have been hid up from the foundation of the world from you… be unfolded…”

Final System States

Suppose that you want to determine the final pressure in a containment building after suffering a primary system pipe break (LOCA). Develop expressions used to find the pressure of the containment building after the transient concludes and the coolant has finished leaking from containment.

First, define initial state as state 1, and final state as state 2.



Assumptions

1. Air behaves as an ideal gas
2. Thermodynamic equilibrium has been reached at time t_2.
3. Neglect impact of gravity and kinetics.
4. Exothermic heat from zirconium/water reaction hasn't been generated yet
5. Heating from structures is negligible.

Solved by Balance Equations

- Total Volume in Containment:
  - $V_c = V_a + V_{wc1} + V_{wpd}$
    - V_c = total containment volume
    - V_a = total volume of air in containment
    - V_{wc1} = total water vapor volume in containment at state 1
    - V_{wpr} = total primary water volume in the primary system
    - V_{wpd} = total primary water volume discharged to containment

- Total Volume in Containment is constant:

$$\frac{d\left(V_a + V_{wc1} + V_{wpd} + V_{wpr}\right)}{dt} = 0$$

Energy Balance

- $E_{c2} - E_{c1} = \dot{Q}_{decay} + \dot{Q}_{chem} + \dot{Q}_{structures}$ (0, 0)
- Energy distribution changes
  - Inside primary to containment + primary
  - Thermo. eq. i.e. $u_{p1} \neq u_{c1}$, but $u_{p2} = u_{c2}$
- $E_1 = m_{wp}u_{wp1} + m_c u_{c1} + m_{wa}u_{wa1} + m_a u_{a1}$
- $E_2 = (m_{wp} + m_c + m_{wa})u_{w2} + m_a u_{a2}$
- Thus balance becomes:
  - $(m_{wp} + m_c + m_{wa})u_{w2} + m_a u_{a2} - m_{wp}u_{wp1} + m_c u_{c1} + m_{wa}u_{wa1} + m_a u_{a1} = \dot{Q}_{decay}$

Thermodynamics

- Remember, h = CpT+h$_o$, u=CvT+u$_o$
- Therefore:
  - $m_a \Delta u + (m_{wp} + m_c + m_{wa})u_{w2}$-$m_{wp}u_{wp1}$-$m_c u_{c1}$-$m_{wa}u_{wa1} = \dot{Q}_{decay}$
  - Becomes
  - $m_a C_v (T_2 - T_{a1}) + (m_{wp} + m_c + m_{wa})u_{w2}$-$m_{wp}u_{wp1}$-$m_c u_{c1}$-$m_{wa}u_{wa1} = \dot{Q}_{decay}$

Known

calculated

  - 1 eqn, 4 unknowns:
    - m_a, T_2, m_{wa}, u_{w2}

Additional Equations…

- Relative humidity, ∅
  - $\emptyset = \frac{P_{wa}}{P_{sat}(T_a)}$
  - $P_1 = P_{a1} + P_{wa1} = P_{a1} + \emptyset P_{sat}(T_a)$
- Ideal Gas Law:
- $m_{a1} = \frac{P_{a1}V_{a1}}{R_a T_{a1}}$, $R_a = \frac{R}{A}$
- $m_{a1} = \frac{\left(P_1 - \emptyset P_{sat}(T_{a1})\right)V_{a1}}{R_a T_{a1}}$

Known

- $m_{wa1} = \frac{\left(\emptyset P_{sat}(T_{a1})\right)V_{a1}}{R_w T_{a1}}$

Water Final Energy

- $V_c = V_w + V_a = (m_{wp} + m_{wc} + m_{wa})\hat{v}_{w2} + V_a$
- In PWR: $V_c \cong V_a$; $P_2 = P_{w2} + P_{a2} = P_{w2} + \frac{R_a T_{a2} m_{a2}}{V_{a2}}$
- 2 paths:
  - Saturated mixture in containment
    - $u_{w2} = u_f(T_2) + x_2 u_{fg}(T_{w2})$
    - $\hat{v}_{w2} = \hat{v}_f(T_2) + x_2 \hat{v}_{fg}(T_2)$
    - $P_{w2} = P_{sat}(T_2)$
  - Superheated steam in containment
    - $u_{w2} = u_w(T_2, P_{w2})$
    - $\hat{v}_{w2} = \hat{v}_w(T_2, P_{w2})$
    - $P_{w2} = P_{w2}(T_2, P_{w2})$

Solutions

- 5 equations, 5 unknowns
- Iterative solution to find final states (T_2, P_2)
- 2 types of problems:
  1. Design problem – know final P (limiting pressure) solve for V_c required
  2. Performance problem – for a given V_c, solve for final P
- This method is even simpler for single-phase situations found in MSRs/LFRs