HAND CALCULATION: TMLB for a 4-Loop PWR

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Hand Calculation

- **Hand calculation on time when core is uncovered based on an energy balance.**
- **The energy balance consists of:**
  - **Energy transfer to SG**
    - **Energy required to boil-off SG water**
    - **Energy transfer to SG shell**
    - **Energy transfer to SG steam**

Hand Calculation

- **The energy balance consists of:**
  - **Energy transfer to and from the RCS (calculation is divided into five periods):**
    - **Time 0 (t_0) to time t_1 when RCS and pressurizer are water solid.**
    - **Time t_1 to t_2 when RCS and pressurizer are water solid and water is saturated at PORV set point pressure.**
    - **Time t_2 to t_3 when the water level in the hot leg is below the surge line inlet.**
    - **Time t_3 to t_4 when the collapsed water level in the downcomer is at the top of active fuel (TAF).**
    - **Time t_4 to t_5 when the two-phase level in the core is at the top of active fuel.**

Conclusions from this Hand Calculation Exercise

- **MAAP4 sensitivity parameters have little impact on the time when the core is uncovered.**
- **These evaluations demonstrate that the time when the core is uncovered during selected SBO depends on the accident sequence, its duration, and assumed operator actions.**
- **Timing is insensitive to the simplifications in the MAAP model.**

Interval Before Core is Uncovered

- **Assumptions:**
  - **No seal LOCA's**
  - **Pressurizer PORV available**
- **Two cases considered:**
  - **Case 1: Base case, all SGs remain pressurized**
  - **Case 2: 1 SG depressurizes due to a stuck open safety valve (first time the valve actuates).**

Initial Conditions

- **RCS:** $M_{W,PS} = 2.107 \times 10^5$ kg
  $T = 563.75$ K
  $h_{W,PS} = 1292.3$ KJ/kg
  $v_{W,PS} = 1.3677 \times 10^{-3}$ m^3/kg
- **Pressurizer:** $M_{W,PZ} = 1.616 \times 10^4$ kg
  $h_{W,PZ} = 1630$ KJ/kg
  $v_{W,PZ} = 1.684 \times 10^{-3}$ m^3/kg
  $P_{PORV} = 1.604E7$ Pa
- **Total volume of RCS + pressurizer = 332.88 m^3**
- **Steam Generator:** $M_{W,SG} = 4.2616 \times 10^4$ kg
  (secondary side) $h_{W,SG} = 1151$ KJ/kg
  $P_{\text{Safety Valve Set Point}} = 7.34$ MPa
  $T_{sat,Psv} = 289.5°C$
  $h_{st,Psv} = 2767.5$ KJ/kg
  Volume = 187 m^3

Case 1: Base Case, All SGs Pressurized

- **Energy Transfer to SGs**
  - **Energy required to boil-off SG water:**
    - $?U_{W,SG} = M_{W,SG}(h_{st,Psv} - h_{W,SG}) \bullet 4$

      $= 2.755 \times 10^{11}$ J
  - **Energy transfer to SG shell:**
    - $M_{SHELL} = 1.974 \times 10^{5}$ kg
    - Assume: $T_{SHELL,f} - T_{SHELL,t=0} \cong 50$ K

      (based on MAAP4 results)
    - $?U_{SHELL,SG} = M_{SHELL} \bullet C_P \bullet ?T \bullet 4$

      $= (1.974 \times 10^{5})(536)(50) \bullet 4$

      $= 2.116 \times 10^{10}$ J

      (an order of magnitude less than the energy required to vaporize the SG water inventory.)

Case 1: Base Case, All SGs Pressurized

- **Energy transfer to SG steam:**
  - **At the time the core is uncovered,**

    $P_{RCS} \cong P_{PORV\ set\ point} = 1.604 \times 10^7$ Pa

    $T_{sat,Pporv} = 347.5°C$
  - **Assume ? T across SG tube is ~ 6 K.**

    (based on MAAP4 results)
  - $T_{g,SG} = 347.5 - 6 = 341.5$ °C
  - $h_{st,Psv\ \&\ Tg=341.5} = 2978.66$ KJ/kg
  - $?U_{gas} = M_{SG,steam}(h_{st} - h_{st,sat}) = (Volume,SG / v_{st})(h_{st} - h_{st,sat}) \cdot 4$

    $= (187 / 0.033)(2978.66 - 2767.5) \times 1000 \times 4$

    $= (5667)(213.16)\ 4000$

    $= 4.832 \times 10^9$ J

    (also an order of magnitude less than the energy required to vaporize the SG water inventory.)
- **Total energy transfer to SG:**

  $?U_{SG,T} = 2.755 \times 10^{11} + 2.116 \times 10^{10} + 4.832 \times 10^9$

  $= 3.01492 \times 10^{11}$ J

Case 1: Base Case, All SGs Pressurized

- **Energy transfer to and from the RCS**
  - **Time 0 (t_0) to time t_1 when the RCS and pressurizer are water solid.**
    - **Assume pressurizer water $v_{w,PZ}$ stays constant during the period.**
    - $M_{w,PZ} \cdot v_{w,PZ} + M_{w,RCS} \cdot v_{w,t_1} = 332.88\ m^3$

$$v_{w,t_1} = 1.4507 \times 10^{-3}\ m^3/kg$$

$$T_{sat}(v_{w,t_1}) = 310.7°C$$

$$h_{w,t_1} = h_w(T_{sat}(v_{w,t_1})) = 1405.43\ KJ/kg$$

$$?\,U_{t_1-t_0} = M_{w,RCS} \times (h_{w,t_1} - h_{w,t_0})$$

$$= 2.3836 \times 10^{10}\ J$$

($M_{w,RCS}$ has expanded to completely fill the pressurizer with the initial temperature of pressurizer water.)

Case 1: Base Case, All SGs Pressurized

– **Time t_1 to t_2 when water becomes saturated at PORV set point pressure (16.04 MPa).**

- $h_{w,t_2} = 1650$ KJ/kg

  $= h_w (T_{sat} (P_{PORV}))$

- $v_{w,t_2} = 1.7107 \times 10^{-3}$ m^3/kg
- $M_{w,t_2} \bullet v_{w,t_2} = 332.88$ m^3
- $M_{w,t_2} = 1.94587 \times 10^5$ kg

  $? M_{w,t_2-t_1} = (1.616 \times 10^4 + 2.107 \times 10^5) - 1.94587 \times 10^5$

  $= 1.616 \times 10^4 + 1.6113 \times 10^4$

  $? M_{w,RCS} = 1.6113 \times 10^4$

Case 1: Base Case, All SGs Pressurized

– **Time t_1 to t_2 when water becomes saturated at PORV set point pressure (16.04 MPa).**

- **Assume original pressurizer water went out with initial enthalpy and ? $M_{w,RCS}$ with average $h_{w,avg}$ (=(h_{w,t_2} + h_{w,t_1}) / 2).**
- **? U_{avg} = ? $M_{w,RCS}$ • ($h_{w,avg}$ - h_{w,t_1})**

  = 1.97 x 10^9 J

Case 1: Base Case, All SGs Pressurized

– **Time t_1 to t_2 when water becomes saturated at PORV set point pressure (16.04 MPa).**

- $?U_{remaining\ water} = M_{w,t2} \bullet (h_{w,t_2} - h_{w,t_1})$

  $= 4.759 \times 10^{10}$

- $?U_{RCS,t_2-t_0} = ?U_{t_1-t_0} + ?U_{avg} + ?U_{remaining\ water}$

  $= 7.3396 \times 10^{10}$

Case 1: Base Case, All SGs Pressurized

- **Total energy transfer to RCS and SG at t_2 (SG dry & RCS + PZR solid with saturated water).**
  - $?\,U_{T,t_2-t_0} = 3.01492 \times 10^{11} + 7.3396 \times 10^{10}$

    $= 3.7489 \times 10^{11}$ J
  - $\int_0^{t_2} Q_{decay}\,dt = 3.7489 \times 10^{11}$ (ANSI-1979)

$t_2 \cong 8520$ s.

Case 1: Base Case, All SGs Pressurized

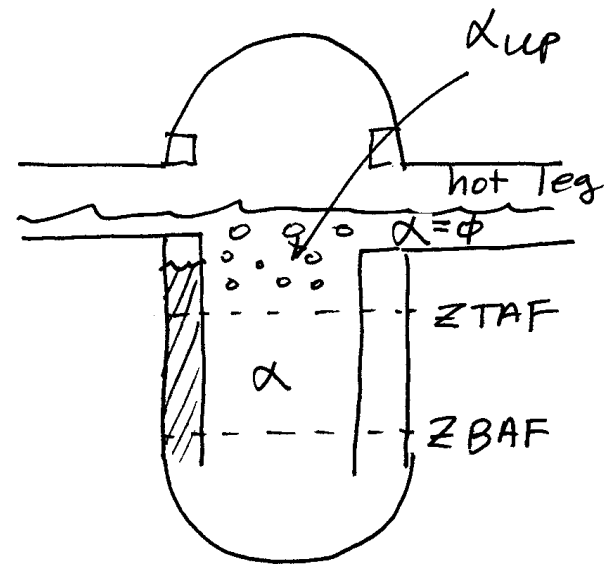
- **Calculate time (t_3) when the water level in the hot leg is below the surge line inlet.**
  - **At t_3, assume:**
    - **Pressurizer is full of water.**
    - **Pump bowl and suction piping is full of water.**
    - **Collapsed water level in the downcomer is equal to the collapsed level in the core. Core and upper plenum have a two-phase pool.**

Case 1: Base Case, All SGs Pressurized

- **Calculate water volume in the downcomer and the core:**

α: average void fraction in the core

α_{up}: void fraction in the upper plenum



$$\alpha = \frac{\dfrac{j_{g,t}}{U_\infty}}{2 + C_o \dfrac{j_{g,t}}{U_\infty}}$$

$$j_{g,t} = \frac{W_{st}}{\rho_{st}\, A_{CORE}} \cong \frac{\left[\dfrac{Q_{decay}}{h_{fg}}\right]}{\rho_{st}\, A_{CORE}} = 0.04146\ \mathrm{m/s}$$

$$U_\infty \cong 1.53\left[\frac{\sigma\, g}{\rho_f}\right]^{1/4} \cong 0.1306\ \mathrm{m/s}$$

α = 0.12048 with C_o = 2.0.

Case 1: Base Case, All SGs Pressurized

- **Void fraction in the upper plenum:**

$$\alpha_{up} = \frac{j_{g,up}}{C_o\, j_{g,up} + U_\infty}$$

where $j_{g,up} = j_{g,t} \cdot \frac{A_{CORE}}{A_{UPPER\ PLENUM}}$

and $C_o = 1.35.$

$\alpha_{up} = 0.1772.$

- **Corresponding water volume in the downcomer and the core:**

$= 36.769 + 51.26 = 88.029\ m^3$

Case 1: Base Case, All SGs Pressurized

- **Total water volume at t_3**

  $= 50.97 + 5.4522 \times 4 + 88.029$

  $= 160.8\ m^3$

- **Total water mass = 94,000 kg**
- **Total steam mass = 18,502 kg**
- **Average quality x = 0.1645**

  $?M_{t_2-t_3} = 1.94587 \times 10^5 - 1.125 \times 10^5$

  $= 82{,}085$ kg

Case 1: Base Case, All SGs Pressurized

– From period t_2 to t_3, assume

- RCS and Pressurizer as one control volume at constant pressure (i.e., at PORV set point).
- System is saturated.
- Write mass & energy conservation equations:

$$dm / dt = - W_{out} \quad (1)$$

$$dU / dt = Q_{in} - Q_{loss} - W_{out}\, h \quad (2)$$

$$dV / dt = 0 = v\, dm / dt + m\, dv / dt \quad (3)$$

where $m = m_w + m_{st}$

$U = m_w u_w + m_{st} u_{st}$

Assume W_{out} goes out with average enthalpy (h).

- At constant pressure,

$$dv / dt = (d (v_f + x\, v_{fg})) / dt = v_{fg}\, dx / dt \quad (4)$$

$$du / dt = u_{fg}\, dx / dt$$

Case 1: Base Case, All SGs Pressurized

– **Equation (2) becomes**

$$m\, u_{fg}\, dx / dt = Q_{in} - Q_{loss} - W_{out}\,(h - u) \qquad (5)$$

– **Combining equations (3), (4), and (5) results in**

$$v\,(-W_{out}) + m\, v_{fg}\,[(Q_{in} - Q_{loss} - W_{out}\,(h - u)) / (m\, u_{fg})] = 0$$

$$\boxed{W_{out} = \frac{v_{fg}\left(Q_{in} - Q_{loss}\right)}{\left(v_f + x\, v_{fg}\right) h_{fg}}}$$

– **Assume Q_{loss} is negligible:**

$Q_{in} \cong 29.8$ MW at ~ 9,000 s.

$$W_{out} = \frac{\int_0^x W_{out}\, dx}{\int_0^x dx}$$

$$= (1/x)\,(Q_{in} / h_{fg})\,[\ln (v_f + x\, v_{fg}) - \ln v_f]$$

where $x = 0.1645$, $v_f = 1.7107 \times 10^{-3}$, $v_{fg} = 7.5293 \times 10^{-3}$, and

$h_{fg} = 936 \times 10^3$

Case 1: Base Case, All SGs Pressurized

$$W_{out} \cong 105.41 \text{ kg/s}$$

$$?\,t_{t_3-t_2} = (?\,M_{t_2-t_3}) / W_{out}$$

$$= 82{,}085 / 105.41 = 778.7 \text{ s}$$

$$t_3 = 8520 + 778.7 = 9298.7 \text{ s}$$

Case 1: Base Case, All SGs Pressurized

- **Calculate time (t_4) when the collapsed water level in the downcomer is at the top of active fuel.**
  - **Water head in the downcomer is equal to the water head in the core**

$$Z_{TAF} = Z_{BAF} + (Z_{TAF} - Z_{BAF})(1 - \alpha) + (Z_{2\phi} - Z_{TAF})(1 - \alpha_{up})$$

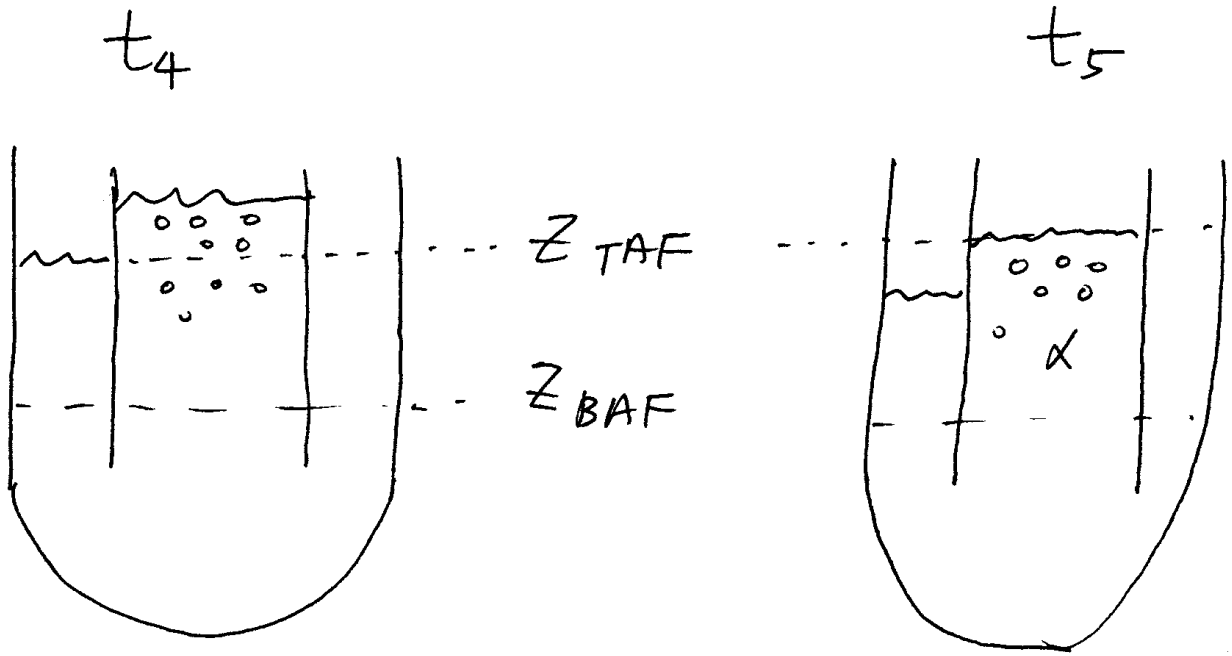
  - **Calculate $Z_{2\phi}$ and water volume in the core**
  - **? $M_{t_3-t_4}$ = (Water mass in the downcomer and the core)$_{t_3}$**

    - (Water mass in the downcomer and the core)$_{t_4}$

    = 8,843 kg
  - **Assume $Q_{decay} \cong 29.8$ MW gives $W_{st} = 31.83$ kg/s**
  - **$t_4 = t_3 + (8843 / 31.83) = 9576$ s**

Case 1: Base Case, All SGs Pressurized

- **Calculate time (t_5) when the two-phase level is at the top of active fuel.**



? $M_{t_4-t_5} \cong$ 3,140 kg.

$t_5 = t_4 + (3140 / 31.8) = 9675$ s

Case 1: Base Case, All SGs Pressurized

- **Effect of RCS heat sinks and fuel in the core.**
  - **Based on MAAP4 results**

    $$?U_{HS} + ?U_{fuel} \cong 8.17 \times 10^9 \text{ J}$$

  - **Assume $Q_{decay} \cong 29.8$ MW, gives**

    $$?t_{HS} = 274 \text{ s}$$

- $t_4^{new} = t_4 + ?t_{HS} = 9576 + 274 = 9850 \text{ s}$
- $t_5^{new} = t_5 + ?t_{HS} = 9675 + 274 = 9949 \text{ s}$

	MAAP4	Hand Calculation
Time when $Z_{WDC} = Z_{TAF}$	9,644 s	9,850 s
Time when $Z_{2\varphi,core} = Z_{TAF}$	9,762 s	9,949 s

Case 2: 1 SG Depressurized

– **Assume SG flashes to 1 bar**

$$m_{w0}\, h_{w,0} = (h_f + x\, h_{fg})_{1bar}\, m_{w0}$$

$$1151 = (419.1 + x\,(2257))$$

$$x = 0.3242$$

$$m_{water\ at\ 1\ bar} = m_{w,0} \bullet (1 - 0.3242)$$

$$= 4.2616 \times 10^4\ (0.6758)$$

$$= 28799.9\ \text{kg}$$

– **Energy required to boil-off $m_{water,1bar}$**

$$?U = 28799.9\ (2257 \times 10^3)$$

$$= 6.5 \times 10^{10}\ \text{J}$$

– **Compare to the previous case with no depressurization,**

$$?U_{low,P} - ?U_{high,P} = 6.5 \times 10^{10} - [(2.755 \times 10^4) / 4]$$

Case 2: 1 SG Depressurized

$$? U_{Case\ 2\ -\ Case\ 1} = -3.875 \times 10^9$$

- This case requires less energy to boil-off the water in the depressurized steam generator.
- Assume $Q_{decay} \cong 29.8$ MW

$$? t = (-3.875 \times 10^9) / (29.8 \times 10^6) = -130 \text{ s}$$

- Assume rest of calculations are identical to those of the previous case.

Case 2: 1 SG Depressurized

– **Then,** $t_4^{new} = 9850 - 130 = 9720$

$t_5^{new} = 9949 - 130 = 9819$

	MAAP4	Hand Calculation
Time when $Z_{WDC} = Z_{TAF}$	9,555 s	9,720 s
Time when $Z_{2\varphi,core} = Z_{TAF}$	9,672 s	9,819 s

Case 2: 1 SG Depressurized

– **Alternate way of calculating α**

- **MAAP: $dj_g / dz = C (1 - \alpha(z))$**
- **Alternate Method: dj_g / dz = Constant (i.e., uniform Q)**
- $\alpha(z) = j_g(z) / (C_o\, j_g(z) + U_\infty)$
- $\alpha_t = j_{g,t} / (C_o\, j_{g,t} + U_\infty)$ **where α_t is a void fraction at the top of the two-phase level.**
- $\alpha = 1 / C_o\, [1 + [(1 - C_o\, \alpha_t) / (C_o\, \alpha_t)]\, \ln (1 - C_o\, \alpha_t)]$ **where α is an average void fraction.**
- $C_o = 1.35$ $\quad \alpha_t = 0.220678$

  $\alpha = 0.112$
- $C_o = 2.0$ $\quad \alpha_t = 0.193$

  $\alpha = 0.1233$

$\therefore$ **Not much different from MAAP's method.**

Lessons Learned from Maanshan Comparisons and these Hand Calculations

- **Hand calculations based on the energy balance are a verification of the MAAP results.**
- **Time when the core is uncovered is insensitive to the void fraction model.**
- **Effect of depressurizing one SG has a second order effect on the time when the core is uncovered.**
- **MAAP4 sensitivity parameters have little impact on the time when the core is uncovered.**
- **These evaluations demonstrate that the time when the core is uncovered during selected SBO depends on the accident sequence, its duration, and assumed operator actions.**
- **Timing is insensitive to the simplifications in the MAAP model.**