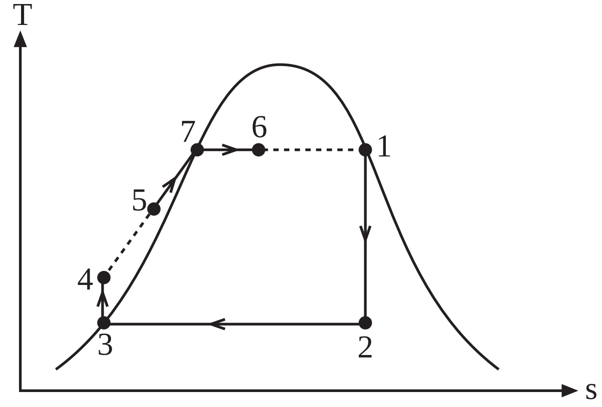
22.312 ENGINEERING OF NUCLEAR REACTORS

Thursday, October 14th, 2004, 9:30 – 11:00 a.m.

OPEN BOOK QUIZ #1 SOLUTIONS 1.5 HOURS

Problem 1 (45%)

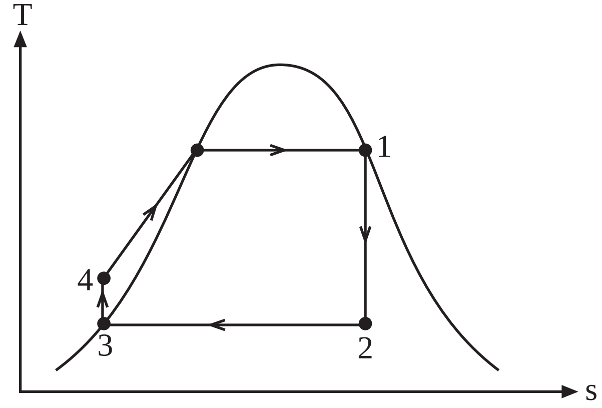
i) The T-s diagram is:



ii) Turbine inlet (**Point 1**): T_1=280°C, P_1=64 bar, h_1=2780 kJ/kg, s_1=5.9 kJ/kg·K, x_1=1.0
Turbine outlet (**Point 2**): T_2=30°C, P_2=0.04 bar, $s_2=s_1$=5.9 kJ/kg·K, $x_2=(s_2-s_{f2})/(s_{g2}-s_{f2}) \approx 0.69$, $h_2=h_{f2}+x_2(h_{g2}-h_{f2}) \approx 1797$ kJ/kg
Condenser outlet (**Point 3**): T_3=30°C, P_3=0.04 bar, h_3=126 kJ/kg, x_3=0
Pump outlet (**Point 4**): $T_4 \approx 30$°C, P_4=64 bar, $h_4=h_3+(P_4-P_3)v_{f4} \approx 132.4$ kJ/kg
Recirculation line (**Point 7**): T_7=280°C, P_7=64 bar, h_7=1236 kJ/kg, x_7=0
Core inlet (**Point 5**): P_5=64 bar, $h_5=0.1\cdot h_4+0.9\cdot h_7 \approx 1126$ kJ/kg
Core outlet (**Point 6**): T_6=280°C, P_6=64 bar, $h_6=h_{f6}+0.1\cdot(h_{g6}-h_{f6}) \approx 1390$ kJ/kg

Thermal efficiency = $(W_{turb}-W_{pump})/Q_{in} = [0.1(h_1-h_2)-0.1(h_4-h_3)]/(h_6-h_5) \approx 37\%$
or, equivalently, $=1-Q_{out}/Q_{in} = 1-0.1(h_2-h_3)/(h_6-h_5) \approx 37\%$

iii) The T-s diagram is:



Cite as: Jacopo Buongiorno, course materials for 22.312 Engineering of Nuclear Reactors, Fall 2007.
MIT OpenCourseWare (http://ocw.mit.edu/), Massachusetts Institute of Technology. Downloaded on [DD Month YYYY].

The thermal efficiency = $(W_{turb}-W_{pump})/Q_{in} = [(h_1-h_2)-(h_4-h_3)]/(h_1-h_4) \approx 37\%$, i.e., identical to the cycle with recirculation. This is expected because recirculation does not change either the net work done by the cycle or the external heat input to the cycle.

iv) Advantages of using cycle without recirculation:

- No steam separator, no recirculation line, thus lower capital cost

Disadvantages of using cycle without recirculation:

- Lower water density in the core, thus worse moderation
- Large temperature rise in the core, bad for thermal stresses (will learn more on this subject later in the course)
- Worse heat transfer (will learn more on this subject later in the course)

Problem 2 (55%)

i) The amount of He initially in the primary system, N_1, is readily obtained from the equation of state:

$$N_1 = \frac{P_{1i} V_1}{RT_{1i}} \approx 250{,}000 \text{ mol} \qquad (1)$$

where P_{1i} (=7 MPa) and T_{1i} (=673 K) are the initial pressure and temperature in the primary system, respectively, and V_1 (=200 m^3) is the primary system volume.
Similarly, the amount of He initially in the containment, N_2, is found as:

$$N_2 = \frac{P_{2i} V_2}{RT_{2i}} \qquad (2)$$

Where P_{2i} (=0.1 MPa) and T_{2i} (=300 K) are the initial pressure and temperature in the containment, respectively. However, the containment volume, V_2, is unknown. When the large break LOCA occurs, the gas inventories in the primary system and containment mix; thus the final pressure, P_f (=1.3 MPa), can be related to the gas inventories, the containment volume and the final (unknown) temperature, T_f, as:

$$P_f = \frac{(N_1 + N_2)RT_f}{V_1 + V_2} \qquad (3)$$

Equations 2 and 3 have three unknown (T_f, V_2 and N_2), so a third equation is needed to solve the problem. The conservation of energy for the control volume representing the primary system and containment is:

$$U_f - U_i = 0 \qquad (4)$$

(note that the decay heat addition is negligible because we are to assume that instantaneous equilibrium is achieved). With reference to the two gas inventories, Equation 4 can be rewritten as:

$$(U_{1f} - U_{1i}) + (U_{2f} - U_{2i}) = 0 \quad \text{or} \quad N_1 c_v (T_f - T_{1i}) = N_2 c_v (T_{2i} - T_f) \tag{5}$$

Where c_v is the helium specific heat. Then T_f is readily obtained as:

$$T_f = \frac{N_1 T_{1i} + N_2 T_{2i}}{N_1 + N_2} \tag{6}$$

Substituting Equation 2 and 6 in Equation 3, and solving for V_2, the following result is obtained:

$$V_2 = \frac{R N_1 T_{1i} - P_f V_1}{P_f - P_{2i}} \approx 950 \text{ m}^3 \tag{7}$$

And back-substituting in Equation 2 and 6, N_2 (≈38,100 mol) and T_f (≈623 K) can be found.

ii) Indicating with $\dot{Q}_o$ (=300 MW) the nominal reactor power, the pressure (and temperature) in the containment will continue to rise until the emergency cooling system capacity (=$0.02\dot{Q}_o$) matches the decay heat rate (=$0.06\dot{Q}_o t^{-0.2}$). Thus, solving for t, one obtains:

$$t_{peak} = \left(\frac{0.06}{0.02}\right)^{1/0.2} \approx 243 \text{ s} \tag{8}$$

where t_{peak} is the time at which pressure and temperature peak. The net heat input to the containment, Q, between t=0 and t=t_{peak} can be calculated as:

$$Q = \int_0^{t_{peak}} (0.06\dot{Q}_o t^{-0.2} - 0.02\dot{Q}_o) dt \approx 364.5 \text{ MJ} \tag{9}$$

The energy equation yields:

$$(N_1 + N_2) c_v (T_{peak} - T_f) = Q \tag{10}$$

And the peak temperature is:

$$T_{peak} = T_f + \frac{Q}{(N_1 + N_2) c_v} \approx 724 \text{ K} \tag{11}$$

So the peak pressure is:

$$P_f = \frac{(N_1 + N_2) R T_{peak}}{V_1 + V_2} \approx 1.5 \text{ MPa} \tag{12}$$

iii) Advantages:

- Lower loads on the containment.

- Can reduce containment thickness, which results in lower capital costs.

Disadvantages:
- Release of potentially radioactive gas to the environment, depending on the efficiency of the filter.
- If the vent valve failed open, the containment would lose its function.