Thermodynamic Analysis of a PWR Plant

The PWR plant operates under the conditions - Table.

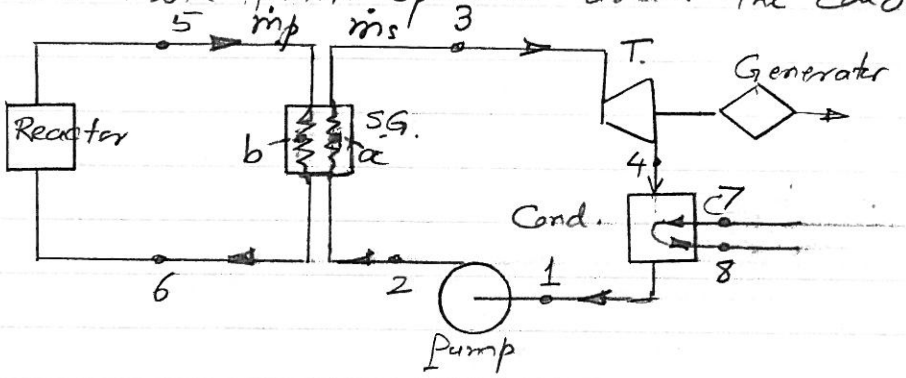


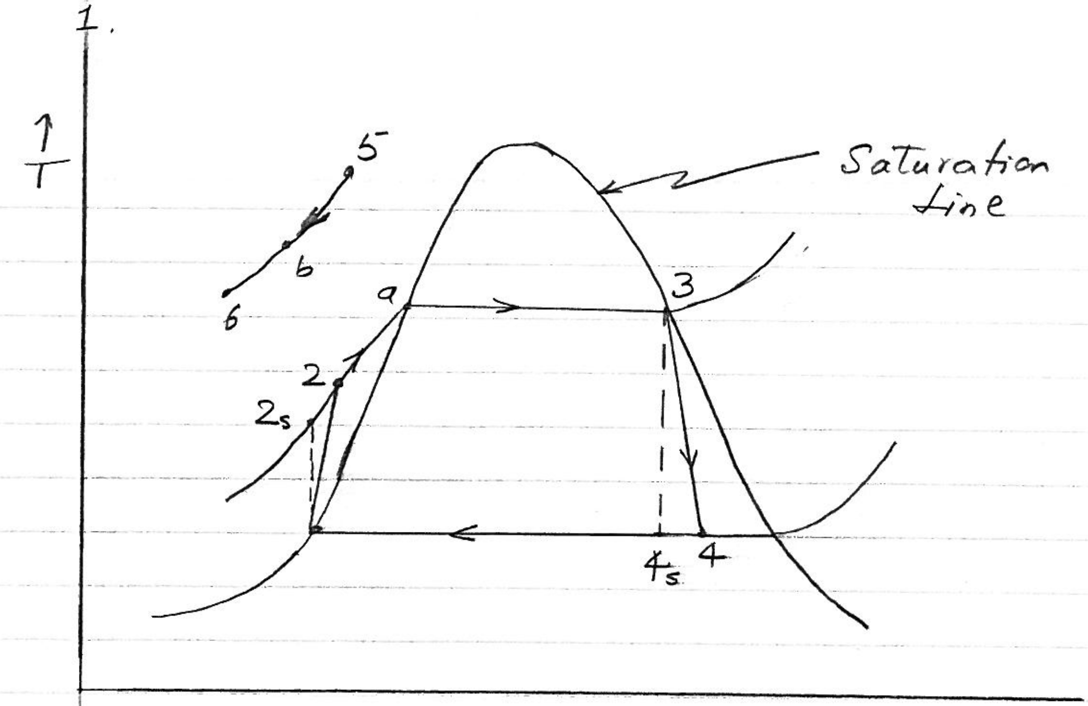
Table: PWR-Operating Conditions.

State	Temp. (°K)	Pressure (kPa)	Condition
1	—	6.89	Satu. Liquid
2	—	7750	subcooled. liquid.
3	—	7750	saturated vapor
4	—	6.89	Two-phase mixture
5.	599	15,500	subcooled liquid
6	565	15,500	"
7			"
8			"
a	—	7750	satu. liquid
b	$T_a + 26 (T_a + 14.4)$	15,500	Subcooled liquid

Assume turbine and pump have isentropic efficiences of 85%.

1 Draw T-s diagram
2 computes $\dot{m}_p / \dot{m}_s$
3 Computer nuclear plant thermodynamic efficiency
4 Compute cycle thermal efficiency

1.



T-s diagram for PWR-cycle.

2.

$$\frac{\dot{m}_p}{\dot{m}_s} = \frac{h_3 - h_a}{\bar{c}_p[T_5 - (T_a + \Delta T_p)]}$$

Steam Tables: $h_3 = h_g$ (sat. at 7750 kPa) $= 2.771$ MJ/kg

$h_a = h_f$ (" ,) $= 1.309$ MJ/kg

T_a = sat. at 7750 kPa $= 566.0°K$

Hence.

$$\frac{\dot{m}_p}{\dot{m}_s} = \frac{2.77\times10^6 - 1.309\times10^6}{5941[599 - (566+14.4)]} = 13.18$$

3. The nuclear plant thermodynamic efficiency (ξ)

$$\xi = \frac{h_3 - h_4 + h_1 - h_2}{h_3 - h_2}$$

From S.T: $h_1 = h_f$ (sat at 6.89 kPa) $= 0.163$ MJ/kg)

$$h_2 = h_1 + \frac{h_{2s} - h_1}{\eta_p} \qquad \left(\eta_p = \frac{h_{2s} - h_1}{h_2 - h_1}\right)$$

$$h_4 = h_3 - \eta_T(h_3 - h_{4s}) \qquad \left(\eta_T = \frac{h_4 - h_3}{h_3 - h_{4s}}\right)$$

State 2:

$s_{2s} = s_1 = 557$ J/kg·K.

$P_{2s} = P_2 = 7.75$ MPa.

$\therefore$ $h_{2s} = 0.170 \text{ MJ/kg}$

$$h_2 = 0.163 + \frac{0.170 - 0.163}{0.85} = 0.171 \text{ MJ/kg}.$$

State 4: $s_{4s} = s_3 = 5758 \text{ J/kg°K}$

$$x_{4s} = \frac{s_{4s} - s_f}{s_{fg}} = \frac{5756 - 555.2}{7723.7} = 0.674$$

$$h_{4s} = h_f + x_{4s} h_{fg} = 0.163 + 0.674\,(2.421)$$

$$= 1.79 \text{ MJ/kg}$$

$$h_4 = h_3 - \eta_T (h_3 - h_{4s}) = 2.771 - 0.85(2.771 - 1.79)$$

$$= 1.94 \text{ MJ/kg}.$$

$$\xi = \frac{2.771 - 1.94 + 0.163 - 0.171}{2.771 - 0.171} = 0.317 //$$

4. thermal efficiency.

$$\eta_{th} = \frac{\dot{W}_{n,act}}{\dot{Q}_{th}}$$

$$\eta_{th}/_{c.v.\,1} = \eta_{th}/_{c.v.\,1} = \xi_{c.v.\,1}.$$

Efficiency can be increased by

1. increasing pressure (and temperature) at which energy in supplied
2. decreasing pressure (and temperature) at which energy is rejected.

Maximum useful work:

$$\dot{W}_{u,max} = \sum_{i=1}^{I} \dot{m}_i (h - T_0 s)_i + \left(1 - \frac{T_0}{T_s}\right)\dot{Q}$$

lost work or irreversibility

$$\dot{W}_{lost} \equiv \dot{I} = -T_0 \sum_{i=1}^{I} \dot{m}_i s_i - \frac{T_0}{T_s}\dot{Q} = T_0 \dot{S}_{gen}.$$

For adiabatic condition ie, $\dot{Q} = 0$ and $\left(\frac{dW}{dt}\right)_{normal} = 0$

Case I. $\dot{W}_{shaft} \neq 0$,

$$\dot{W}_{shaft} = \sum_{i=1}^{I} \dot{m}_i h_i = \dot{W}_{actual}$$

irreversibility: $\dot{I} = -T_0 \sum \dot{m}_i s_i = T_0 \dot{S}_{gen.}$

$$\dot{I} = \dot{W}_{u,max} - \dot{W}_{actual} = \sum \dot{m}_i (h_i - T_0 s)_i - \dot{W}_{shaft}$$

$$\therefore \quad \dot{W}_{u,max} = \sum_{i=1}^{I} \dot{m}_i (h_i - T_0 s)_i$$

Case II $\dot{W}_{shaft} = 0$

$$\sum_{i=1}^{I} \dot{m}_i h_i = 0 = \dot{W}_{actual}.$$

$$\dot{W}_{u,max} = \dot{I} = -T_0 \sum_{i=1}^{I} \dot{m}_i s_i = T_0 \dot{S}_{gen}.$$

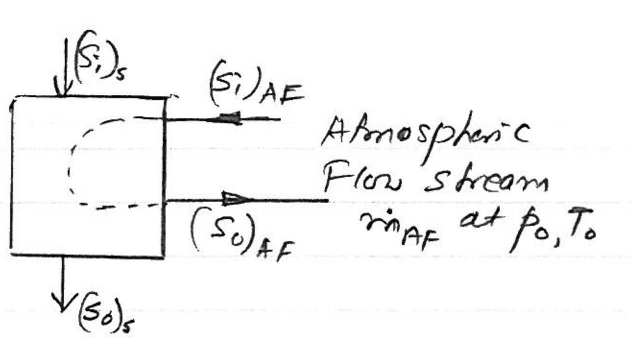
1. Turbine & Pump: These have finite shaft work and single inlet & outlet streams.

$$\therefore \quad \dot{I} = \dot{m} T_0 (s_{out} - s_{in})$$

and $\quad \dot{W}_{u,max} = \dot{m}\left[(h_{in} - h_{out}) - T_0 (s_{in} - s_{out})\right]$

2. Steam generator and condenser. These have zero shaft work and two inlet & exit streams.

Condenser



$$\dot{I} = \dot{W}_{u,max} = T_0\left(\sum_{k=1}^{2} \dot{m}_{out,k}\, s_{out,k} - \sum_{k=1}^{2} \dot{m}_{in,k}\, s_{in,k}\right)$$

for condenser.

$$\dot{I} = \dot{m}_{AF} T_0 \Delta s_{AF} + \dot{m}_s T_0 \Delta s_s$$

$\because \quad T ds = dh \quad$ — constant p.

$$\dot{m}_{AF} T_0 \Delta s_{AF} = \dot{m}_{AF} \Delta h_{AF}$$

$$\dot{m}_{AF} \Delta h_{AF} = -\dot{m}_s \Delta h_s \quad \leftarrow \text{heat balance}$$

$$\dot{m}_{AF} T_0 \Delta s_{AF} = -\dot{m}_s \Delta h_s$$

$$\therefore \quad \dot{I}_1 = T_0\, \dot{m}_s \left[-\frac{\Delta h_s}{T_0} + \Delta s_s\right]$$

$$\dot{I} = T_0\, \dot{m}_s \left[-\frac{h_1 - h_4}{T_0} + s_1 - s_4\right] \longleftarrow$$

also $\quad \dot{I} = \dot{m}_{in}(h_{in} - T_0 s_{in}) - \dot{m}_{out}(h_{out} - T_0 s_{out})$

3. Reactor Irreversibility.

$$\dot{I}_R = \dot{m}_p T_0 (s_{out} - s_{in})_R$$

4. Plant Irreversibility.

$$\dot{W}_{u,max\,\text{reactor plant}} = -\left[\frac{\partial(U - T_0 S)}{\partial t}\right]_{\text{reactor plant}} + \dot{m}_{AF}\left[(h_{in} - h_{out}) - T_0(s_{in} - s_{out})\right]_{AF}$$

$$-\left[\frac{\partial(U - T_0 S)}{\partial t}\right]_{rp} = -\left[\frac{\partial(U - T_0 S)}{\partial t}\right]_r = -\left(\frac{\partial U}{\partial t}\right)_r.$$

$$\dot{I}_R = T_0 \dot{S}_{gen} \quad \text{and} \quad \dot{Q} = 0, \quad \left(\frac{\partial S}{\partial t}\right)_r = \dot{m}_p(s_{in} - s_{out}) + \frac{\dot{I}_R}{T_0} = 0$$

$$\left(\frac{\partial U}{\partial t}\right)_r = \dot{m}_{in} h_{in} - \dot{m}_{out} h_{out}$$

$$= \dot{m}_p (h_{out} - h_{in})_{SGp.} = \dot{m}_s (h_{in} - h_{out})_{SGs.}$$

$$\therefore \left[\dot{W}_{u,max}\right]_{rp} = \dot{m}_p (h_{in} - h_{out})_{SGp} = \dot{m}_s (h_{out} - h_{in})_{SGs.}$$

$$\dot{I}_{rp} = -T_0 \sum_{i=1}^{I} \dot{m}_i s_i = T_0 \dot{m}_{AF} (s_{out} - s_{in})_{AF}$$

$$\therefore \dot{I}_{rp} = -\dot{m}_s \Delta h_s = \dot{m}_s (h_{in} - h_{out})_{s.}$$

$$\dot{I}_{rp} = \dot{m}_s (h_4 - h_1) \leftarrow$$