Version ES/3

EGT3
ENGINEERING TRIPOS PART IIB

Wednesday 25 April 2018 2.00 – 3.40

Module 4I10

NUCLEAR REACTOR ENGINEERING CRIB

1. (a). Positive impacts:

- Low oxidation → no hydrogen production
- High strength at high temperatures → LOCA and CHF may no longer be an issue.

Negative impacts:

- Brittle → fuel handling procedures may need to be reconsidered, may fail catastrophically.
- Larger fuel-cladding gap → larger thermal resistance and thus higher fuel temperature, thus fission gas release and swelling rate. Maximum fuel temperature may limit power density.
- Lower cladding thermal conductivity → higher fuel temperature, as above.
- No pellet cladding contact → limited burnup.

(b) - Smaller pellet → less fuel, shorter cycle or higher enrichment requirement.

- Smaller pellet → higher H/HM, softer spectrum, higher reactivity, partially or fully compensating for the loss cycle length. On the other hand, may bring the lattice closer to over-moderation condition, thus reducing magnitude of MTC, also MTC potentially positive at lower boron ppm.
- Si and C are better moderators and weaker absorbers → equivalent to higher H/HM with the same effects as above. Higher reactivity may require higher loading of burnable absorbers. On the other hand, burnable absorbers will have higher reactivity worth and higher loading may not be required.

(c) Rim effect is a result of resonance self-shielding. Slowing down neutrons diffusing from moderator into fuel are preferentially absorbed in outer layer of fuel pellet by U^{238} atoms leading to Pu239 accumulation near the surface. When U^{235} is mostly depleted, most power is produced by Pu fission which is concentrated in the rim.

Substituting q''': $\frac{1}{r}\frac{d}{dr}\left(k(T)r\frac{dT}{dr}\right) + 200 + 1.5\times10^3\, r^4 = 0$

$$\frac{d}{dr}\left(k(T)r\frac{dT}{dr}\right) + 200\, r + 1.5\times10^3\, r^5 = 0$$

Integrating once: $k(T)\, r\frac{dT}{dr} + 100\, r^2 + 250\, r^6 + C_1 = 0$

Symmetry BC: $\frac{dT}{dr} = 0$ at $r = 0$, thus $C_1 = 0$

Integrating again and evaluating at $r = R$: $\int_{T(R)}^{T_{max}} k\,(T)\, dT = 50\, R^2 + 125\,\frac{R^6}{3}$

Substituting expression for k and integrating: $10^{-5}\, T_{max}^2 + 0.09\, T_{max} - 30.275 = 13.151$

$T_{max} = 511$ °C, the second root is unphysical.

2. (a). 1) compensate for excess reactivity to assure reactor criticality for prolonged periods of time between refuelling outages. Reduce reliance on control rods which distort power distribution. Reduce reliance on soluble boron, which may make MTC positive.
2) improve power distribution, helping to meet the design thermal constraints, also throughout the core irradiation campaign. Larger amount of poisons can be loaded to regions with high power peaking.

(b). Ideal burnable poison:
- burnup rate matching reactivity loss of the fuel.
- complete burn up, no residual reactivity penalty, negligible absorption of resulting nuclides.
- chemically compatible with surrounding materials of the original as well as resulting poison nuclides.
- minimal displacement of fuel.
- minimal effect on thermal conductivity, fission gas release and other fuel properties.

(c). Power density: PWR (~100 W/cm^3), BWR (~50 W/cm^3) since boiling reduces hydrogen atoms density, more space is needed for the coolant to provide the necessary moderation, thus, larger core, CANDU (~10 W/cm^3) moderator is less efficient, therefore large volume is needed. AGR (~3 W/cm^3) even less efficient moderator, also safety requirement to make fuel melting – in-credible.
Discharge burnup: PWR/BWR – similar (~50 MWd/kg) achieved through fuel enrichment (~3-5%) and multi-batch refuelling in 2-4 batches. AGR (~20 MWd/kg) slightly enriched fuel, possibility of on-power refuelling channel by channel. CANDU (7-10 MWd/kg), natural uranium, continuous online refuelling.
Cycle length: PWR/BWR (12-24 months), AGR few days (~5 channels per month), CANDU few hours (~4-8 bundles per day). Explanation as above.

(d).

(i) Total energy generated during the cycle:

E = P_0 * CF * t = 3000×(3×0.8/2+3×0.8+3×1.0+3×0.8)*365.25/12 = 8.218*10^5 MWd

B = E/M_{HM} = 8.218*10^5 / 10^5 = 8.218 MWd/kg

(ii)

$P = \Phi\, \sigma_f\, N_{U235}\, E_f;$

Number of U235 atoms at end of life:

$$N_{U235} = \frac{P_0 \times 0.8}{\Phi\, \sigma_f\;\, E_f} = \frac{3000\times10^6 \times 0.8}{4.5\times10^{14} \times 35\times10^{-24}\;\, \times 200\times10^6\times\, 1.602\times10^{-19}} = 4.756\times10^{27}\text{atoms.}$$

Number of fissions per cycle = E/(E_f) = $\frac{8.218*10^5*10^6*24*3600}{200\times10^6\times\, 1.602\times10^{-19}}$ = 2.217×10^{27}

Initial number of U235 atoms = $4.756\times10^{27} + 2.217\times10^{27} = 6.972\times 10^{27}$

Mass of 1 U235 atom = 0.235 kg/mole / N_A = 3.9024 *10^{-25} kg

Initial U235 mass = $6.972\times 10^{27} \times\; 3.9024\; \times 10^{-25} = 2720.75$ kg

Initial enrichment = 2720.75 / 100,000 = 2.72 %

3. (a). Decay heat of the core is the sum of decay heats of three batches. Neglect refuelling outage shutdowns for once and twice burnt batches. Operating time for each batch: (0+1) M = 365.25/12*24*60*60 = 2,629,800 s
(12+1) M = 365.25/12*24*60*60*13 = 34,187,400 s
(24+1) M = 365.25/12*24*60*60*25 = 65,745,000 s

$P(t_s) = 0.066 \times P_0(t_s{}^{-0.2} - (t_s + \tau_s)^{-0.2}),\ t_s = 60\ s,$

$P_0 = \frac{3000}{3} = 1000\ MW$ – assume equal power share between the batches.

$P_1 = 25.6693\ MW, \quad P_2 = 27.0466\ MW, \quad P_3 = 27.2985\ MW$

$P = P_1 + P_2 + P_3 = 80.0144\ MW$

(b). Saturation temperature at 150 bar: T_{sat} = 342 °C
Therefore, core outlet: T_{out} = 342 – 100 = 242 °C

$$\dot{m} = \frac{P}{h_2 - h_1} = \frac{80.0144 \times 10^6}{(1048.4 - 858.1) \times 10^3} = 420.9\ kg/s$$

(c). Pumping power: W = $\Delta p \frac{\dot{m}}{\rho}$

Assume, most pressure losses are due to friction and gravity – reasonable assumption since temperature change is small, thus density and velocity change is also small.

ρ = 850 kg/m^3; A = $(1.5^2 - \pi(0.5)^2)/10^4 = 1.464*10^{-4}$ m^2; μ=0.00152 Pa s

v = $\frac{\dot{m}}{\rho A} = \frac{420.9}{850*1.464*10^{-4}*256*193}$ =0.0684 m/s;

D=4A/P_h = $4*1.464*10^{-4}/(2\pi r)$= 0.01865 m;

Re=ρVD/μ = 713 – thus the flow is laminar; Friction factor: f=64/Re =0.08978;

Δp_{fric}= $\rho V^2/2$ * L/D * f = 38.25 Pa.

$\Delta p_{gravity}$ = ρgL = 850*9.8*4 = 33,200 Pa – conservative because thermal expansion is neglected but bonus for mentioning/discussing the buoyancy effect.

Δp_{shock} = K *$\rho V^2/2$ ~ 2K, thus small and can also be neglected even though K is not provided, but it is on the order of 1.

W_{total} = 2 $\Delta p \frac{\dot{m}}{\rho}$ = 2*(33,200+38)*421/850 = 32.9 kW

(d).

Passive decay heat removal systems rely on natural phenomena such as gravity and natural convection of coolant. Examples:

- ESBWR Isolation condenser – boiling in the core produces steam which is directed into a heat exchanger where it is condensed and flows back into the pressure vessel under gravity. The HX is submerged in a large pool of water.
- AP-1000 – evaporation of coolant and steam escape into containment, condensation on the containment walls and flow into IRWST and back to the core. The containment is cooled by water from a large tank on the roof or natural convection of air.
- PRISM – heat is conducted to the guard vessel wall, where it is removed by natural convection of air.

4. (a). PWR: Saturated steam (no superheat), feed water pre-heat, moisture separator/re-heater between high and low-pressure turbines, reheat is achieved by mixing part of the fresh (high temperature steam) with high pressure turbine outlet steam. Maximum steam temperature is limited to about 300C due to limit on primary pressure. Achievable efficiency ~33%. Additional efficiency losses due to primary water pumping. Steam generators are big, expensive and tricky to maintain (occasionally need replacement and need sophisticated testing/maintenance procedures)
BWR: similar to PWR but no SG and less pumping requirement due to buoyancy. Similar cycle efficiency. No expensive SGs but maintenance of power cycle equipment is complicated by radiation fields.
AGR: High superheated steam temperatures ~550 C/150 bar, reheat between turbine stages, feedwater heaters, as a result – highest thermal efficiency among all commercial reactors – 42%. Boilers are non-replaceable and considered a life-limiting component for the plant (cracking is an issue).

(b). If the power up-rate is small, the plant may not require any modifications at all if the safety case can be made through more detailed analysis and corresponding recapture of unnecessarily high safety margins.

(i). - Primary coolant flow rate may need to be increased by 5% to keep ΔT core the same. Primary pumps may need upgrade by more than 5% because frictional Δp is non-liner function of flow rate.
- Higher power means high heat flux and linear power, reducing MDNBR and increasing fuel central line temperature. If challenged, the total number of fuel pins in the core and their diameter may need to be reassessed.
- Higher fuel temperature will lead to higher negative Doppler reactivity and will need compensation through higher enrichment or sacrifice some cycle length and burnup. Also, higher fuel temperature could have negative impact on fuel performance characteristics such as swelling and fission gas release.

(ii) - Steam Generator surface area needs to be adjusted by 5%, otherwise MTD across the SG would need to be higher, which would reduce power conversion efficiency.
- Consider whether steam turbine would be able to cope with higher steam flow, and if not, would need to be upgraded.
- all other pumps, piping and heat exchangers would need to be able to cope with higher flow rates, if the main cycle parameters (p,T) at different points throughout the cycle are to be maintained and assure that there is no loss to power conversion efficiency.

(c)

Relevant data from steam tables.

At 60 bar:

$h_4 = h_{g4}$ =2764.6 kJ/kg, $s_4 = s_{g4}$ = 5.89 kJ/kg/K

At 0.1 bar:

h_{1f}=191.8kJ/kg, h_{1g}=2583.9kJ/kg, v_1=0.00101 m^3/kg, s_{g1}=8.15 kJ/kg/K, s_{f1}=0.65 kJ/kg/K

$h_2 = h_1 + v\,\Delta p = 0.00101\ (6 - 0.001)*10^6 = 197.9$ kJ/kg

$x_5 = (s_4 - s_{g5})/(s_{g5} - s_{f5}) = (5.89 - 0.65)/(8.15 - 0.65) = 0.699$

$h_{5s} = h_f + x\, h_{fg} = 191.8 + 0.699\ (2583.9 - 191.8) = 1863$ kJ/kg

ideal cycle efficiency: $h_{ideal} = ((h_4 - h_{5s}) - (h_2 - h_1)) / (h_4 - h_2) = 35.4\%$

turbine efficiency: $h_T = (h_4 - h_5)/(h_4 - h_{5s})$

$h_5 = h_4 - h_{real}\ (h_4 - h_2) - (h_2 - h_1) = 2784.6 - 0.33(2784.6 - 197.9) - 6.06 = 1924.9$ kJ/kg

$h_T = (h_4 - h_5)/(h_4 - h_{5s}) = (2784.6 - 1924.9)/(2784.6 - 1863) = 93.3\%$

ENGINEERING TRIPOS PART IIB 2017-2018
ASSESSOR'S REPORT, MODULE 4I10

Q1 Accident Tolerant Fuel Cladding

7 attempts, Average mark 12/20, Maximum 15, Minimum 5.
The question was part descriptive, part computational. The first part asked to list and explain the effects of using a new cladding material on reactor safety, neutronic and thermal-hydraulic performance. This part was not trivial and required analysis and understanding of broad range of nuclear fuel design issues. Naturally, it created a wide distribution of marks. The second part required deriving a relatively standard analytical solution of heat conduction equation in cylindrical coordinates with given radial distribution of heat source and temperature dependent thermal conductivity. Most of the candidates had no difficulty with this part.

Q2 Reactor design features and fission energy

8 attempts, Average mark 11.5/20, Maximum 18, Minimum 5.
This was a relatively broad question, testing understanding of multiple concepts. The first part was about the role of burnable poisons in a reactor and considerations in their choice. The next part required basic knowledge of various reactor types and their relative operational advantages and drawbacks. The final part required basic manipulation of reactor power/energy produced and their relation to the amount of fissile material needed and rate of fission reactions. This was the most popular question with most students getting the main ideas correctly.

Q3 Decay heat removal

4 attempts, Average mark 11.5/20, Maximum 12, Minimum 11.
This was the least popular question, probably due to seemingly high computational load. It required working out the amount of decay heat a reactor produces after shutdown and calculating operational characteristics (flow rate and power) of a pump needed to circulate the coolant to remove this heat. The main problems with this question were: failing to account for different core residence time of different fuel batches when calculating the decay heat and forgetting to include pressure losses other than friction into the overall cooling loop pressure drop.

Q4 Comparison of reactor power conversion cycles

8 attempts, Average mark 12.9/20, Maximum 17, Minimum 6.
This was another popular question attempted by nearly all candidates. The descriptive part required understanding of unique features of power conversion cycle arrangements for the most popular current reactor types. Then, the question asked for qualitative analysis of implications a small core power uprate would have on the primary and secondary circuits of a PWR. This was the least straight forward part with a wide range of depths of analysis. The last part required a standard thermodynamic analysis of a simple Rankine cycle with which most students had no difficulties.