4I11 CRIB 2016-17

1 (a)

Gen4 objectives: Economics, waste, non-proliferation, safety and sustainability.

- High core outlet coolant temperature allows achieving high thermal efficiency of power conversion – good for economics.

- High core outlet coolant temperature allows using nuclear heat for industrial processes directly (e.g. hydrogen production) or for efficient energy storage (as heat). – good for economics and sustainability.

- TRISO fuel can withstand high temperatures in accidents therefore HTRs are designed to be inherently safe ("walk away safety") with passive shutdown and residual heat removal. – good for safety.

- HTRs can in principle accommodate various fuel cycles (breeding or burning, U or Th) – good for sustainability, economics and waste.

- Pebble bed HTRs have on-line refuelling, therefore can potentially be more fuel efficient than LWRs – good for economics and sustainability.

- Salt-cooled HTRs would operate at low pressure therefore would have one less type of driving force for potential faults (good for safety) and would have cheaper vessel (good for economics). [15%]

(b) - TRISO particles have large surface to volume ratio, therefore less strong self-shielding and higher absorption rate in U238 which would lower the reactivity.

- High resonance absorption and high operating temperatures would lead to a large reactivity decrement due to the core heat up.

- The core dimensions are not driven by minimisation of leakage but by decay heat removal limits through pressure vessel wall and control rods shutdown capability since they are inserted in radial reflector. This leads to tall and thin core with relatively high leakage. [15%]

(c) Linear power along axial direction follows the power density: $q'(z) = q_0{}'cos\left(\frac{\pi z}{H}\right)$

Find q_0 from normalisation to total power: $\int_{-H/2}^{H/2} q_0' \, cos\left(\frac{\pi z}{H}\right) dz = Q; \quad q_0' = Q\frac{\pi}{2H}$

Integrating along the axial height: $T_{He}(z) = T_{in} + \frac{q_0'}{\dot{m}c_p}\int_{-H/2}^{z} cos\left(\frac{\pi z}{H}\right) dz$

$$T_{He}(z) = T_{in} + \frac{q_0'}{\dot{m}c_p}\frac{H}{\pi}\left(1 + sin\left(\frac{\pi z}{H}\right)\right) = T_{in} + \frac{Q}{2\dot{m}c_p}\left(1 + sin\left(\frac{\pi z}{H}\right)\right)$$

[30%]

(d)

$\dot{m}c_p(T_{out} - T_{in}) = Q$ $\dot{m} = \frac{Q}{c_p(T_{out}-T_{in})} = \frac{600 \times 10^6}{5200\,(900-400)} = 230.8\ \frac{kg}{s}$ [10%]

(e)

Pebble surface temperature at z: $T_s(z) = T_{He}(z) + \Delta T_{film}(z)$

Core power density at z: $q'''(z) = \frac{q'(z)}{\pi R^2} = \frac{q'_0}{\pi R^2} cos\left(\frac{\pi z}{H}\right) = \frac{Q}{2HR^2} cos\left(\frac{\pi z}{H}\right)$

Power per pebble at z: $Q_P(z) = q'''(z) \times \frac{V_P}{Packing\ fraction}$

$$Packing\ fraction = \frac{V_P \times N_P}{V_{core}} = \frac{\frac{4}{3}\pi R_P^3 \times N_P}{\pi R^2 H} = 0.6$$

$$Q_P(z) = \frac{Q}{2HR^2} cos\left(\frac{\pi z}{H}\right) \times \frac{\frac{4}{3}\pi R_P^3}{0.6}$$

Heat flux at pebble surface at z: $q''(z) = \frac{Q_P(z)}{4\pi R_P^2}$

Film ΔT at z: $\Delta T_{film}(z) = \frac{q''(z)}{h} = \frac{Q_P(z)}{4\pi R_P^2 h} = \frac{\frac{Q}{2HR^2} cos\left(\frac{\pi z}{H}\right) \times \frac{\frac{4}{3}\pi R_P^3}{0.6}}{4\pi R_P^2 h} = \frac{QR_P}{3.6\ HR^2 h} cos\left(\frac{\pi z}{H}\right)$

$T_s(z) = T_{in} + \frac{Q}{2\dot{m}c_p}\left(1 + sin\left(\frac{\pi z}{H}\right)\right) + \frac{QR_P}{3.6\ HR^2 h} \cos\left(\frac{\pi z}{H}\right)$

$T_s(5) = 400 + \frac{500}{2}\left(1 + sin\left(\frac{5\pi}{20}\right)\right) + 600 \times 10^6 \times \frac{0.03}{3.6 \times 20 \times 1.5^2 \times 1000} cos\left(\frac{5\pi}{20}\right) = 905.3\ °C$

[30%]

Q1 High-Temperature Reactors technology
10 attempts, Average mark 12.6/20, Maximum 16, Minimum 7.
Reasonably popular question aiming at testing the knowledge on advantages of HTRs and their unique design features. The first part was answered well by most candidates. In computational part, the heat balance calculations were also generally successful. One common mistake made by many candidates was failing to account for non-uniform axial power distribution when calculating pebbles surface temperature at a given elevation.

2

(a) Effects of temperatures on reactivity

Fuel: The Doppler effect is negative (in that an increase in temperature reduces reactivity). The effect is larger at low fuel temperatures. [10%]

Thermal expansion has little effect because the fuel adheres to the cladding, the temperature of which is controlled by the coolant.

Temperature in the core: An increase has a negative effect because it causes radial and axial expansion of the structure, increasing neutron leakage. There may be an additional negative effect due to outward bowing of the subassembly wrappers because the radial flux gradient makes them hotter on the side facing the core centre. This depends on the way the wrappers are supported and located. [10%]

There are both positive and negative effects of a decrease in coolant density:

- positive at the core centre because of decreased moderation of the neutron energy spectrum (with an additional small effect due to loss of neutron capture)
- negative at the periphery of the core due to increased leakage.

Outlet temperature: Depending on the design of the above-core structure there may be a negative effect due to expansion of the control rod supports to insert the absorbers farther into the core.

[10%]

(b) (i) Core outlet temperature

Power = coolant flow-rate × specific heat capacity × temperature rise

$\Delta T = 3\times10^9 / (1.5 \times 10^4 \times 1.26 \times 10^3) = 158.7$ K

Outlet temperature = 400 + 158.7 = 558.7 °C [5%]

(ii) For LBE $c_p = 0.142$, thus

$\Delta T = 3\times10^9 / (1.5 \times 10^4 \times 0.142 \times 10^3) = 1408$ K

This is much higher than the structural materials can tolerate. [10%]

(iii) Choice of flow rate

- Minimise pumping power (low velocity)
- Minimise ΔT to maximise power conversion efficiency (high velocity)
- Maintain oxide protective layer (in lead/LBE, low velocity)
- Keep T outlet under structural limits (creep, vibrations) and below boiling (in Na)
- Keep ΔT such that reactivity coefficients are within desired limits [10%]

(c) Reactivity changes

At steady state $\delta\rho = 0 = \delta\rho_{in} + A\delta P/P + B\delta F/F$

First test $\delta F/F = 0.01$, $\delta P/P = 0$, $\delta\rho_{in} = -0.02\$ \rightarrow B = 2\$$

Second test $\delta F/F = 0$, $\delta P/P = -0.01$, $\delta\rho_{in} = -0.05\$ \rightarrow A = -5\$$

(i) Power change given by $0 = 0 - 5 \times \delta P/P + 2 \times 0.01 \rightarrow \delta P/P = 0.004 = 0.4\%$

$P = 0.004 \times 3000$ MW = 12 MW [15%]

(ii) $P = F \times c \times \Delta T \rightarrow \delta(\Delta T)/\Delta T = \delta P/P - \delta F/F = 0.004 - 0.01 = -0.006$

Decrease in $\Delta T = 158.7 \times 0.006 = 0.95$ K → outlet temperature = 557.75 °C [10%]

(d) Allowable flow-rate

Maximum allowable temperature difference across the core

$\Delta T = 600 - 400 = 200$ K, 42 K or 26% more than design.

A 1% increase in flow rate causes a 0.6% reduction in ΔT,

so a 26% increase would be caused by a flow reduction of 26/0.6 = 43%. [20%]

This is a large linear extrapolation from the test conditions, over a range in which the response might not be linear. It also neglects any overshoot which would be negligible in the tests but might be significant for a large change.

Q2 Sodium-cooled fast reactors safety

6 attempts, Average mark 11.2/20, Maximum 16, Minimum 6.

The question tested the students' understanding of passive safety concept in the design of fast spectrum sodium-cooled reactors. The most difficulty was encountered when calculating the quasi-static reactivity balance with coefficients that had to be derived from the experiments described in the problem statement. Here, again, the students were able to perform well on basic heat balance-type parts of the question. Another differentiator was the part asking to justify the choice of coolant flow rate in liquid metal-cooled fast reactors.

3 **(a) [15%]**

Disadvantages include:

1. Tritium is radioactive and easily taken into biological material as tritiated water, making it a safety concern
2. DT reactions generate high-energy neutrons that irradiate materials
3. Tritium production is exceptionally expensive at the levels of kg and must be bred in the reactor in large quantities
4. Highly mobile and difficult to contain, requiring complex facilities and invariably leading to losses/escape (and safety issues)

(b) [25%]

The fuel requirement is

3.0E+09 J/s / (1.60218E-19 J/eV) / (1.76E+07 eV/atom) x (3.0160492 amu/atom) x

x (1.66054E-24 g/amu) = 5.33 mg per second = 168 kg /year

At 30,000 $ per gram this is 5.04 billion dollars per year.

(c) [20%] Lithium6 has an exothermic (n,t) reaction with a large thermal cross section, producing heat that can be extracted for energy. Lithium7 has an endothermic (n,nt) reaction that removes heat but also leaves a neutron free to undergo further reactions.

(d) [20%]

A good heterogeneous arrangement would include mostly Li6 to take advantage of the high cross-section, but would place enriched Li7 at the front of the blanket to use the larger threshold cross section and reduce heating near the blanket surface while also not decreasing the neutron flux through (n,nt).

Use of a neutron multiplier is essential, for example beryllium or lead. Also, moderation of the neutrons to increase the Li6 cross-section is required. Water, heavy water or carbon may be suggested, or any material with high elastic cross-section, low mass and low non-elastic cross-section.

(e) [20%]

HCPB: Helium cooled pebble bed. Ceramic lithium pellets with beryllium moderator and helium coolant. Beryllium provides a high neutron multiplication. Tritiated helium purge loop isolated from a helium coolant loop that draws heat.

HCLL: Helium cooled lithium lead. Lithium lead eutectic acts as tritium breeding material and multiplier with Pb(n,Xn) reactions. LiPb continuously passed through tritium extraction with potential for Li6 replenishing. Secondary helium coolant loop extracts heat.

WCLL: Water cooled lithium lead. Similar to HCLL with pressurised water loop and subsequently different operating temperatures/conditions.

DCLL: Complex water + He coolant system with lithium lead otherwise similar to WCLL and HCLL.

Q3 Fusion technology: tritium breeding

13 attempts, Average mark 14.1/20, Maximum 17, Minimum 12.

This was the most popular question attempted by all candidates. Most candidates have successfully managed to calculate the fuel requirements and costs for a generic fusion reactor and identify the key features of breeding tritium from Li-6 and Li-7 isotopes. Somewhat wider range of answers was observed in parts of the question asking to list considerations in tritium breeding blanket design and provide examples followed by justification of materials choices and their arrangement.

4

(a) [30%]

Ohmic heating. The coils within the central pole of the torus act like the primary coil of a transformer, with the secondary loop being the plasma. This induces a current in the plasma which generates heat.

Neutral beam injection. Particles of fuel are ionised, accelerated and then neutralised through interaction with gas before being shot into the plasma, injecting energy as they have considerably higher energy than the plasma average.

Ion cyclotron (Radio-frequency) heating. Radio antennae are positioned within the plasma-facing walls of the reactor and used to launch waves at the characteristic energies of the ion cyclotron frequency of the plasma, adding energy to those ions.

(b) [35%]

The student must use:

1. The definition of confinement time as the ratio of contained energy of the plasma to the heat loss: $\tau = \frac{W_{th}}{P_{loss}}$
2. The definition of the plasma energy content as the kinetic energy of heavy ions and electrons, as $W_{th} = 3n_e kTV$ and thus $P_{loss} = \frac{W_{th}}{\tau} = \frac{3n_e kTV}{\tau}$
3. Definition of fusion rate as $n_D n_T \langle\sigma v\rangle = \frac{1}{4} n_e{}^2 \langle\sigma v\rangle$,
   thus fusion power is $P_{fus} = n_D n_T \langle\sigma v\rangle E_n V = \frac{1}{4} n_e{}^2 \langle\sigma v\rangle E_n V$ and
   Charged particles heating power: $P_{ch} = \frac{1}{4} n_e{}^2 \langle\sigma v\rangle E_{ch} V$
4. Fusion charged particle power must be greater than losses: $P_{ch} > P_{loss}$
   Thus, $\frac{1}{4} n_e{}^2 \langle\sigma v\rangle E_{ch} V > \frac{3n_e\, kTV}{\tau}$ or $n_e \tau > \frac{12\, kT}{E_{ch}\langle\sigma v\rangle}$

It is not the total fusion since the neutrons are not charged and will escape the plasma. It is not only alpha heating (although mostly for DT) as there will be some DD and indeed TT fusion with their respective products.

(c) [20%]

P_{fus} = $n_D \times n_T \times \langle\sigma v\rangle \times V$ = (½ × 1E20)^2 × 1E-22 × 1E3 × (1.602E-19 J/eV) × 1.76E7 eV/fusion

= 705 MW fusion

Only about 20% is carried by the charged alpha particle, so 141 MW to the plasma.

(d) [15%]

Use the Lawson criterion derived/provided in (b) with the supplied information and note the charged particle energy is 3.5 MeV. This results in:

1.0 E21 m^{-3} s, which is greater than 3.42857E+20 m^{-3} s, so yes, the alpha heating is sufficient.

Q4 Plasma physics

10 attempts, Average mark 13.8/20, Maximum 20, Minimum 8.

Also, a popular question testing the understanding of fusion reactor principles such as confinement time and conditions for self-sustainable plasma. Most candidates correctly identified and explained principles of operation for conventional plasma heating methods. Less straightforward parts required basic knowledge of concepts such as plasma stored energy, rate of energy loss, fusion reactor rate, which resulted in a range of answers.