Engineering Tripos Part IIB 2015 - 4I11 - Crib

1.

Answer:

a)

(Sources of significant advantage are underlined.)

Property	Sodium	Lead-bismuth	Comment
Density	Low	High	Lighter, cheaper structure for Na-cooling Tendency of fuel and components to float in Pb-Bi
Cost	Cheap	Expensive	Possible supply problem for Bi
Corrosion	Slight	Severe	Pb corrodes steels. Surface preparation required
Experience	Extensive	Slight	Pb-Bi has been used only in Soviet nuclear subs
Moderation	Slight	Negligible	The moderating effect of Na leads to the possibility of a gain in reactivity on loss of coolant
Flammability	Severe	None	All major Na components have to be provided with leak jackets and fire-suppression systems
Reaction with water	Severe	Mild	Na steam generators have to have extensive protection against leaks. Secondary Na circuits required
Radioactive products	^{24}Na	^{210}Po	Production on ^{24}Na requires secondary Na circuits ^{210}Po is highly toxic
Boiling point	Low	High	Boiling is a real safety concern in sodium cooled Reactors. Not an issue in LBE cooled reactors
Thermal Expansion	Reasonable	Good	LBE is better than Na at removing heat by natural circulation

Compared with other coolants all liquid metals have the advantage that they operate at low pressure, and the disadvantage that they are opaque.

b)

(i) Na coolant

Power = Flow rate x Specific heat x Temperature rise.

Flow rate = 3 x 10^9 / 1260 x 200 = 11900 kg/s

Flow rate = Area x Velocity x Density

Velocity = 11900 / (π x 1^2 x 0.5) x 817 = 9.3 m/s

(ii) Pb-Bi coolant

Flow rate = 3 x 10^9/ 142 x 200 = 105600 kg/s

Velocity = 105600 / π x 0.5 x 10100 = 6.7 m/s

(iii) If velocity = 4 m/s, flow rate = 105600 x 4 / 6.7 = 63040 kg/s

Temperature rise = 200 x 105600 / 63040 = 335 K

Inlet temperature = 550 – 335 = 215 °C

(iv) The alternatives are:

- To accept the low feedwater temperature and the concomitant low thermal efficiency and reduced output of the steam plant,
- To increase the coolant flow area in the core by increasing its diameter, incurring the expense of a larger reactor vessel, or
- To reduce the power of the core, accepting the reduced output of the plant.

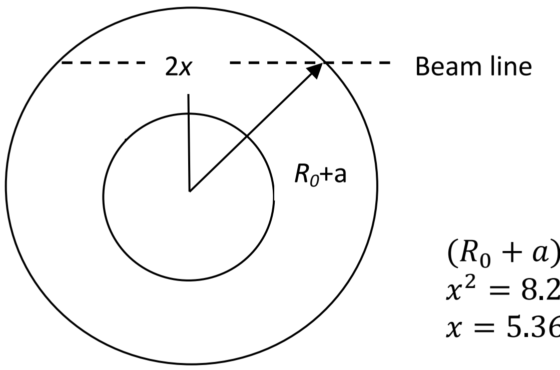
2

Answers:

(a) A tokamak is a magnetically-confined plasma. Charged particles are confined by the magnetic field and cannot cross it. Therefore, injected particles must be neutralised before injection. The NBI system generates ions in the ion source, accelerates them to high energy, then passes them through a neutraliser and into the tokamak. To avoid damage to components, any un-neutralised particles are steered into an ion dump before the particle beam reaches the tokamak. The neutral high-energy particles are then re-ionised by the plasma and confined as they thermalise, heating the plasma in turn.

(b) Positive-ion beams strip electrons from the source gas to form positive ions. Negative-ion beams add electrons to the source gas. Since the former process is easier than the latter, positive-ion beams have a much higher ionisation efficiency. However, the charge-exchange process to re-attach the electrons and neutralise the ions has an energy-dependent cross-section and becomes inefficient much above 150keV, limiting the injection energy that can be achieved with positive ion beams. Negative-ion beams have a much larger cross-section for neutralisation and so are capable of much higher injection energies (up to 1000keV for ITER). For efficient current-drive and good penetration into a power-plant plasma, high energies are desirable and so negative-ion beams are required.

(c) From a simple geometrical construction the beam half-path length to the centre of the plasma is given by:



$$(R_0 + a)^2 = {R_0}^2 + x^2$$
$$x^2 = 8.2^2 - 6.2^2$$
$$x = 5.36m$$

A section through the toroid.

Thus the path all the way though the plasma is x = 10.7m.
The total collision cross-section is $3\times10^{-18}/1000 = 3\times10^{-21}$
and so the decay length (λ) is $3\times10^{-21}\times10^{20} = 0.3$m.
The shine-through fraction is then $n_b(10.7)/n_b(0) = \exp(-10.7/0.3) = 3.2\times10^{-16}$.

(d) This is clearly low enough that almost no power is transferred to the vessel wall opposite the beam injector. If the plasma was less dense, the beams would impinge on the wall and damage it, both through heat load and erosion from the impact of energetic particles.

3.

Answers:

(a) Five categories of challenges has been identified that the current generation of reactors is facing. These are:

- Economics
- Safety
- Sustainability of resources
- Environment and waste management
- Non-proliferation

In each of those categories, Gen-III reactors are gradually approaching their limits.

Therefore, entirely new type of reactors is needed if they were to offer fundamental advantages in each of the categories as compared to the existing Gen-III reactors.

(b) High core outlet temperature is desirable for increasing the power plant thermodynamic efficiency and thus improving its economics. Furthermore, high temperatures can be used in various industrial processes e.g. hydrogen and synthetic liquid fuels production which would allow expanding the nuclear energy use beyond generation of electricity. Therefore, it is beneficial for achieving better economics and, indirectly, for the environment since wider range of nuclear energy applications would reduce carbon emissions and help addressing the climate change.

(c) There two main reasons.

1. Gases have low density. Therefore, large volumes are needed to remove given heat with reasonable pumping power.
2. Gases have little or no moderating effect. Therefore, separate moderator material is needed. Since gases are usually chosen to allow high temperature applications, water or other hydrogen compounds as moderators are not practical. The next practical choice is graphite which is much less efficient – higher atomic weight, thus it would occupy a large volume fraction of the core reducing its power density.

(d)

(i) Peak fuel temperature will occur in core centre at the peak axial power location (core mid-plane).

Counting from the vessel surface, the total temperature drop will consist of

Peak Fuel T = 400 °C + pebble bed ΔT + pebble clad ΔT + fuel zone ΔT + kernel ΔT

kernel ΔT = $q_{kernel}''' \frac{R_{kernel}^2}{6k_{UO2}}$

fuel zone matrix ΔT = $q_{fuel\ zone}''' \frac{R_{fuel\ zone}^2}{6k_{graphite}}$

pebble outer clad ΔT = $\frac{Q_{pebble}\,(R_2-R_1)}{4\pi k_{graphite} R_1 R_2}$

pebble bed ΔT = $\frac{q_{peak}'}{4\,\pi\,k_{PB}}$

$q_{peak}'(z=0)$ = $\frac{P_{reactor}}{H} \times \frac{\pi}{2}$

Core power density = $\overline{q'''} = \frac{P_{reactor}}{V} = \frac{P_{reactor}}{\pi R^2 H}$

Peak pebble power density (z=0) = $\overline{q'''} \times \frac{\pi}{2} \times \frac{1}{f} = \frac{P_{reactor}}{\pi R^2 H} \times \frac{\pi}{2f} = \frac{P_{reactor}}{2\,R^2 H f}$

(*f* is the packing fraction and π/2 is peak to average ratio for cosine)

Peak pebble power Q_{pebble} = $\frac{P_{reactor}}{2\,R^2 H f} \times V_{pebble}$

Peak pebble fuel zone power density = $\frac{P_{reactor}}{2\,R^2 H f} \times \frac{V_{pebble}}{V_{fuel\ zone}}$

Peak fuel kernel power density = $\frac{P_{reactor}}{2\,R^2 H f} \times \frac{V_{pebble}}{N_{kernels} V_{kernel}}$

$$1600 - 400 = \frac{P_{reactor}}{2\,R^2 H f} \times \frac{V_{pebble}}{N_{kernels} V_{kernel}} \times \frac{R_{kernel}^2}{6k_{UO2}} + \frac{P_{reactor}}{2\,R^2 H f} \times \frac{V_{pebble}}{V_{fuel\ zone}} \times \frac{R_{fuel\ zone}^2}{6k_{graphite}} +$$

$$+ \frac{P_{reactor}}{2\,R^2 H f} \times V_{pebble} \times \frac{(R_2-R_1)}{4\pi k_{graphite} R_1 R_2} + \frac{\frac{P_{reactor}}{H} \times \frac{\pi}{2}}{4\,\pi\,k_{PB}}$$

$$P_{reactor} = \\ = \frac{1200}{\frac{1}{2\,R^2 H f} \frac{V_{pebble}}{N_{kernels} V_{kernel}} \frac{R_{kernel}^2}{6k_{UO2}} + \frac{1}{2\,R^2 H f} \frac{V_{pebble}}{V_{fuel\ zone}} \frac{R_{fuel\ zone}^2}{6k_{graphite}} + \frac{1}{2\,R^2 H f} V_{pebble} \frac{(R_2 - R_1)}{4\pi k_{graphite} R_1 R_2} + \frac{1}{8\,H\,k_{PB}}}$$

$P_{reactor} = 2.879 \times 10^6$ W which is 1% of the nominal power, thus

$P_{reactor} = 2.879 / 0.01 = 287.9$ MW

(ii)

For an annular core with central reflector, the heat conduction path becomes shorter reducing the ΔT across the pebble bed. Therefore, higher power per unit height can be tolerated in loss of flow accident. However, the volume occupied by the pebble bed will be smaller leading to higher power per pebble, thus leading to higher temperature drop across the pebble at full power operation which may become a limiting factor.

Smaller pebble bed volume will lead to smaller fuel inventory and would require either higher enrichment of faster pebbles feed rate. This could be partially compensated by better moderation due to the presence of additional graphite in the central reflector.

Central reflector will also flatten the radial power distribution.

4.

Answers:

(a) Deuterium can be obtained from water — approximately 1 in 2,000 hydrogen atoms are deuterium. They must be separated from H^1 (*protium*) through isotopic separation methods but are not in short supply.
Tritium has a short half-life (~12 years) and does not naturally occur in any abundance, so it must be manufactured. This is done by using the neutrons from nuclear processes to split lithium into tritium (and helium, plus energy and possibly another neutron depending on the isotope of lithium). This process is planned to be carried out in a *breeding blanket* around the reactor.
Potential problems include ensuring that there are enough neutrons available to breed sufficient tritium to make the reactor self-sustaining (this requires neutron multipliers in the blanket, such as lead or beryllium); extracting the tritium on a reasonable timescale from the blanket to avoid having to store too much of it on site.
Also, there is the potential for competition for lithium resources from *e.g.* battery manufacturers, especially if technologies like electric cars become popular.

(b) The D-T fusion reaction produces 17.6 MeV of energy, which is
$17.6\times10^{6}\times6.02\times10^{23}\times1.602\times10^{-19} = 1.7\times10^{12}$J per mole of reaction.
If we take an average person's lifetime to be 70 years at 20kWh/day, that is 2.1×10^{12}J, or about 4.125 moles assuming a power cycle conversion efficiency of 30%.
The mass of tritium required is then $4.125 \times 3.016 = 12.4$ g of tritium.

(c) D-T is used principally because the cross-section σ and reaction rate $\langle\sigma v\rangle$ are much higher and peak at a lower temperature than other fusion reactions (*e.g.* D-D, D-He^3, p-B). It is also nearly the most energetic (D-He^3 gives 18.3MeV). However it requires T to be produced and produces energetic neutrons, which cannot help to sustain the reaction and damage the materials of the reactor and produce activated nuclear waste.

(d) Of the two main aneutronic alternatives with decent reaction rates, D-He^3 requires high temperatures (300-400 keV, helped by all the energy ending up in charged particles and so able to heat the plasma) but has a lower overall reaction rate and requires He^3 - not available in abundance on Earth and usually made through the decay of T and so requiring T but without the neutrons from the reaction to produce it. p-B fusion is attractive and aneutronic and the fuels are cheap and abundant on Earth, but requires very high temperatures (>1000 keV), at which the Bremsstrahlung radiation losses are much greater than the fusion power, requiring an optically-thick plasma to be engineering if the plasma is not to cool itself out of burn.
Achieving these temperatures is also beyond current capabilities.

4I11 – Assessor's comments

Q1 Fast Reactors engineering and design
This question required understanding of considerations for liquid metal coolant choice in fast spectrum reactors. The list of considerations is quite long which created a reasonable distribution of marks for this question. The computational part on certain aspects of fast reactor design appeared to be trivial and was completed correctly by nearly all candidates.

Q2 Neutral Beam plasma heating
This was fusion reactors engineering question. It was aimed at assessing the knowledge of purpose and operating principles of Neutral Beam plasma heating system. Most students showed good conceptual understanding of these principles. The computational part required familiarity with fusion reactors terminology so that assumptions regarding the system geometry could be made. The marks on this part varied depending on how successful the students were in making these assumptions.

Q3 High Temperature Gas-cooled Reactors design and safety
Nearly half of the marks on this question were awarded for calculation of temperature distribution in a gas-cooled reactor in order to estimate its maximum achievable power given a safety constraint. The amount of computing, although simple in principle, is what probably deterred most of the student from attempting this question. The remaining half of the marks were awarded for qualitative discussion of advanced (Generation IV) reactor systems in general and high temperature gas-cooled reactors' features in particular.

Q4 Fusion reactors fuel choices
This question assessed understanding of issues of availability and practicality of using different elements/isotopes as a fuel for fusion reactors. Most of the students showed good understanding of these issues. Tritium production and associated engineering challenges were appropriately identified and calculation of tritium requirements mostly correctly performed.