Q1

(a) $\eta = \dfrac{\nu \Sigma_f}{\Sigma_a}$

$\Sigma_f = \sum_i \sigma_{fi} N_i = \sigma_{f235} N_{235}$

$\Sigma_a = \sum_i \sigma_{ai} N_i = \sigma_{a235} N_{235} + \sigma_{a238} N_{238}$

$\sigma_a = \sigma_c + \sigma_f$

$N_{235} = eN$ where e is the enrichment and N is the number density of U atoms

$N_{238} = (1-e)N$

$\therefore \quad \Sigma_f = 580eN$

$\therefore \quad \Sigma_a = (107 + 580)eN + (2.75 + 0)(1-e)N = (2.75 + 684.25e)N$

$\therefore \quad \eta = \dfrac{\nu \Sigma_f}{\Sigma_a} = \dfrac{2.43 \times 580eN}{(2.75 + 684.25e)N} < 1.5$

$\therefore \quad 1409.4e < 1.5 \times (2.75 + 684.25e) = 4.125 + 1026.375e$

$\therefore \quad 383.025e < 4.125 \quad \Rightarrow \quad e < 0.01077$ [20%]

(b)
$$\frac{dn}{dt} = -\nabla.\underline{j} + (\eta - 1)\Sigma_a \phi + S$$

Steady-state: $\qquad \therefore \quad \dfrac{dn}{dt} = 0$

Source-free: $\qquad \therefore \quad S = 0$

Fick's law: $\qquad \underline{j} = -D\nabla\phi$

$\qquad \therefore \quad 0 = -\nabla.(-D\nabla\phi) + (\eta-1)\Sigma_a\phi$

If D is constant: $\qquad \therefore \quad 0 = D\nabla^2\phi + (\eta-1)\Sigma_a\phi$

$\qquad \therefore \quad \nabla^2\phi + B_m^2\phi = 0 \qquad$ where $B_m^2 = \dfrac{(\eta-1)\Sigma_a}{D}$

The above also assumes the reactor is homogeneous.

The material buckling B_m^2 is a function of the material properties of the core constituents.

The geometric buckling B_g^2 is a function of the geometry of the core, e.g. for a cylindrical

core $B_g^2 = \left(\dfrac{2.405}{R_0}\right)^2 + \left(\dfrac{\pi}{H_0}\right)^2$. For criticality, $B_m^2 = B_g^2$. [25%]

(c) In spherical geometry: $\qquad \nabla^2 = \dfrac{1}{r^2}\dfrac{d}{dr}\left(r^2\dfrac{d}{dr}\right)$

$\qquad \therefore \quad \dfrac{1}{r^2}\dfrac{d}{dr}\left(r^2\dfrac{d\phi}{dr}\right) + B_m^2\phi = 0$

Now $\dfrac{1}{r^2}\dfrac{d}{dr}\left(r^2\dfrac{d\phi}{dr}\right)=\dfrac{1}{r^2}\left(2r\dfrac{d\phi}{dr}+r^2\dfrac{d^2\phi}{dr^2}\right)=\dfrac{1}{r}\left(2\dfrac{d\phi}{dr}+r\dfrac{d^2\phi}{dr^2}\right)=\dfrac{1}{r}\left(\dfrac{d^2(\phi r)}{dr^2}\right)$

$$\therefore\quad \dfrac{1}{r}\left(\dfrac{d^2(\phi r)}{dr^2}\right)+B_m{}^2\phi=0$$

$$\therefore\quad \dfrac{d^2(\phi r)}{dr^2}+B_m{}^2(\phi r)=0$$

By inspection this has a general solution:

$$\therefore\quad \phi r = A\sin(B_m r)+C\cos(B_m r)$$

$$\therefore\quad \phi = \dfrac{A}{r}\sin(B_m r)+\dfrac{C}{r}\cos(B_m r)$$

The boundary conditions are $\phi = \phi_1$ at $r = R_1$ and $\phi = 0$ at $r = R_2$.

$$\therefore\quad \phi_1 = \dfrac{A}{R_1}\sin(B_m R_1)+\dfrac{C}{R_1}\cos(B_m R_1)$$

and

$$0 = \dfrac{A}{R_2}\sin(B_m R_2)+\dfrac{C}{R_2}\cos(B_m R_2)$$

$$\therefore\quad C = -A\dfrac{\sin(B_m R_2)}{\cos(B_m R_2)}$$

$$\therefore\quad \phi_1 R_1 = A\sin(B_m R_1)-A\dfrac{\sin(B_m R_2)}{\cos(B_m R_2)}\cos(B_m R_1)$$

$$\therefore\quad \phi_1 R_1\cos(B_m R_2) = A\left[\sin(B_m R_1)\cos(B_m R_2)-\sin(B_m R_2)\cos(B_m R_1)\right]$$

$$\therefore\quad \phi_1 R_1\cos(B_m R_2) = A\sin[B_m(R_1-R_2)]$$

$$\therefore\quad A = -\dfrac{\phi_1 R_1\cos(B_m R_2)}{\sin[B_m(R_2-R_1)]}$$

$$\therefore\quad C = \dfrac{\phi_1 R_1\sin(B_m R_2)}{\sin[B_m(R_2-R_1)]}$$

$$\therefore\quad \phi = -\dfrac{\phi_1 R_1\cos(B_m R_2)}{\sin[B_m(R_2-R_1)]}\dfrac{1}{r}\sin(B_m r)+\dfrac{\phi_1 R_1\sin(B_m R_2)}{\sin[B_m(R_2-R_1)]}\dfrac{1}{r}\cos(B_m r)$$

$$\therefore\quad \phi = \dfrac{1}{r}\dfrac{\phi_1 R_1}{\sin[B_m(R_2-R_1)]}\left[\sin(B_m R_2)\cos(B_m r)-\cos(B_m R_2)\sin(B_m r)\right]$$

$$\therefore\quad \phi = \dfrac{\phi_1 R_1}{r}\dfrac{\sin[B_m(R_2-r)]}{\sin[B_m(R_2-R_1)]}\qquad\qquad [45\%]$$

(d) Use of a reflector will improve (reduce) the form factor, making the power distribution more even, but a reflector also changes the geometric buckling of the core. In this case there is a danger that adding a reflector will make the core critical, which is contrary to the design intent for an ADSR.   [10%]

Principal Assessor's comments:

A very popular question attempted by 90% of candidates. Part (a), which was meant to be straightforward, was done surprisingly badly – many attempts were derailed by calculator errors. Part (b) was done well. Many found part (c) difficult due to poor differential equation solving techniques. A surprisingly large number of candidates tried to apply a boundary condition for $r = 0$, even though this is at the centre of the spallation target rather than part of the subcritical core. Very few candidates spotted the fact that the addition of a reflector might make the core critical.

Q2

(a) $\dfrac{dI}{dt}$ is the rate of change of the iodine-135 population

$\gamma_i \Sigma_f \phi$ is the rate of creation of iodine-135 through fission

$\lambda_i I$ is the rate of decay of iodine-135 to xenon-135

$\dfrac{dX}{dt}$ is the rate of change of the xenon-135 population

$\gamma_x \Sigma_f \phi$ is the rate of creation of xenon-135 through fission

$\lambda_x X$ is the rate of decay of xenon-135 to caesium-135

$\sigma X \phi$ is the rate of transmutation of xenon-135 to xenon-136   [15%]

(b)   In equilibrium $\dfrac{dI}{dt} = 0$ and $\dfrac{dX}{dt} = 0$

$$\therefore \quad \gamma_i \Sigma_f \phi_0 - \lambda_i I_0 = 0 \quad \Rightarrow \quad I_0 = \frac{\gamma_i \Sigma_f \phi_0}{\lambda_i}$$

and

$$\gamma_x \Sigma_f \phi_0 + \lambda_i I_0 - \lambda_x X_0 - \sigma X_0 \phi_0 = 0$$

$$\therefore \quad \lambda_x X_0 + \sigma X_0 \phi_0 = \gamma_x \Sigma_f \phi_0 + \lambda_i I_0$$

$$\therefore \quad X_0 \left[\lambda_x + \sigma \phi_0 \right] = \gamma_x \Sigma_f \phi_0 + \gamma_i \Sigma_f \phi_0 = (\gamma_x + \gamma_i) \Sigma_f \phi_0$$

$$\therefore \quad X_0 = \frac{(\gamma_x + \gamma_i) \Sigma_f \phi_0}{\lambda_x + \sigma \phi_0} \qquad\qquad [10\%]$$

(c)   The variation of the iodine-135 population is governed by

$$\frac{dI}{dt} = \tfrac{1}{2} \gamma_i \Sigma_f \phi_0 - \lambda_i I$$

$$\therefore \quad \frac{dI}{dt} + \lambda_i I = \tfrac{1}{2} \gamma_i \Sigma_f \phi_0$$

By inspection the particular integral is

$$I_{PI} = \frac{\gamma_i \Sigma_f \phi_0}{2 \lambda_i}$$

Also by inspection the complementary function is

$$I_{CF} = A\exp(-\lambda_i t)$$

Therefore the general solution is

$$I = \frac{\gamma_i \Sigma_f \phi_0}{2\lambda_i} + A\exp(-\lambda_i t)$$

The boundary condition is that at $t = 0$, $I = I_0 = \dfrac{\gamma_i \Sigma_f \phi_0}{\lambda_i}$

$$\therefore \quad \frac{\gamma_i \Sigma_f \phi_0}{\lambda_i} = \frac{\gamma_i \Sigma_f \phi_0}{2\lambda_i} + A \quad \Rightarrow \quad A = \frac{\gamma_i \Sigma_f \phi_0}{2\lambda_i}$$

$$\therefore \quad I = \frac{\gamma_i \Sigma_f \phi_0}{2\lambda_i}\left[1 + \exp(-\lambda_i t)\right]$$

[20%]

(d) The variation of the xenon-135 population is governed by

$$\frac{dX}{dt} = \tfrac{1}{2}\gamma_x \Sigma_f \phi_0 + \lambda_i I - \lambda_x X - \tfrac{1}{2}\sigma X \phi_0$$

$$\therefore \quad \frac{dX}{dt} + \left[\lambda_x + \tfrac{1}{2}\sigma\phi_0\right]X = \tfrac{1}{2}\gamma_x \Sigma_f \phi_0 + \lambda_i I$$

$$\therefore \quad \frac{dX}{dt} + \lambda_{eff} X = \tfrac{1}{2}\gamma_x \Sigma_f \phi_0 + \lambda_i I$$

where
$$\lambda_{eff} = \lambda_x + \tfrac{1}{2}\sigma\phi_0$$

Substituting the result for expression for I from (c)

$$\therefore \quad \frac{dX}{dt} + \lambda_{eff} X = \tfrac{1}{2}\gamma_x \Sigma_f \phi_0 + \tfrac{1}{2}\gamma_i \Sigma_f \phi_0\left[1 + \exp(-\lambda_i t)\right]$$

$$\therefore \quad \frac{dX}{dt} + \lambda_{eff} X = \tfrac{1}{2}(\gamma_x + \gamma_i)\Sigma_f \phi_0 + \tfrac{1}{2}\gamma_i \Sigma_f \phi_0 \exp(-\lambda_i t)$$

By inspection the particular integral will be of the form

$$X_{PI} = A + B\exp(-\lambda_i t)$$

$$\therefore \quad -\lambda_i B\exp(-\lambda_i t) + \lambda_{eff}\left[A + B\exp(-\lambda_i t)\right] = \tfrac{1}{2}(\gamma_x + \gamma_i)\Sigma_f \phi_0 + \tfrac{1}{2}\gamma_i \Sigma_f \phi_0 \exp(-\lambda_i t)$$

$$\therefore \quad \lambda_{eff} A = \tfrac{1}{2}(\gamma_x + \gamma_i)\Sigma_f \phi_0 \quad \Rightarrow \quad A = \frac{(\gamma_x + \gamma_i)\Sigma_f \phi_0}{2\lambda_{eff}} \quad \left[= \frac{(\gamma_x + \gamma_i)\Sigma_f \phi_0}{2\lambda_x + \sigma\phi_0}\right]$$

and $\quad \therefore \quad -\lambda_i B + \lambda_{eff} B = \tfrac{1}{2}\gamma_i \Sigma_f \phi_0 \quad \Rightarrow \quad B = \frac{\gamma_i \Sigma_f \phi_0}{2(\lambda_{eff} - \lambda_i)} \quad \left[= \frac{\gamma_i \Sigma_f \phi_0}{2(\lambda_x - \lambda_i) + \sigma\phi_0}\right]$

By inspection the complementary function is

$$X_{CF} = C\exp(-\lambda_{eff} t)$$

Therefore the general solution is

$$X = \frac{(\gamma_x + \gamma_i)\Sigma_f \phi_0}{2\lambda_{eff}} + \frac{\gamma_i \Sigma_f \phi_0}{2(\lambda_{eff} - \lambda_i)}\exp(-\lambda_i t) + C\exp(-\lambda_{eff}t)$$

The boundary condition is that at $t = 0$, $X = X_0 = \frac{(\gamma_x + \gamma_i)\Sigma_f \phi_0}{\lambda_x + \sigma\phi_0}$

$$\therefore \quad \frac{(\gamma_x + \gamma_i)\Sigma_f \phi_0}{\lambda_x + \sigma\phi_0} = \frac{(\gamma_x + \gamma_i)\Sigma_f \phi_0}{2\lambda_{eff}} + \frac{\gamma_i \Sigma_f \phi_0}{2(\lambda_{eff} - \lambda_i)} + C$$

$$\therefore \quad C = \frac{(\gamma_x + \gamma_i)\Sigma_f \phi_0}{\lambda_x + \sigma\phi_0} - \frac{(\gamma_x + \gamma_i)\Sigma_f \phi_0}{2\lambda_{eff}} - \frac{\gamma_i \Sigma_f \phi_0}{2(\lambda_{eff} - \lambda_i)}$$

$$\therefore \quad X = \frac{(\gamma_x + \gamma_i)\Sigma_f \phi_0}{2\lambda_{eff}} + \frac{\gamma_i \Sigma_f \phi_0}{2(\lambda_{eff} - \lambda_i)}\exp(-\lambda_i t)$$

$$+ \left[\frac{(\gamma_x + \gamma_i)\Sigma_f \phi_0}{\lambda_x + \sigma\phi_0} - \frac{(\gamma_x + \gamma_i)\Sigma_f \phi_0}{2\lambda_{eff}} - \frac{\gamma_i \Sigma_f \phi_0}{2(\lambda_{eff} - \lambda_i)}\right]\exp(-\lambda_{eff}t)$$

$$\therefore \quad X = \frac{(\gamma_x + \gamma_i)\Sigma_f \phi_0}{2\lambda_{eff}}\left[1 - \exp(-\lambda_{eff}t)\right] + \frac{\gamma_i \Sigma_f \phi_0}{2(\lambda_{eff} - \lambda_i)}\left[\exp(-\lambda_i t) - \exp(-\lambda_{eff}t)\right]$$

$$+ \frac{(\gamma_x + \gamma_i)\Sigma_f \phi_0}{\lambda_x + \sigma\phi_0}\exp(-\lambda_{eff}t)$$

[45%]

(e)   The time variation of the xenon-135 population means that the poisoning effect due to the xenon also changes with time. If criticality is to be maintained, as implied by the desire for constant flux, then this means that control action (e.g. the moving of control rods) is necessary to compensate for the change in poisoning. In this particular case the xenon-135 population initially rises before falling to its equilibrium level (which is lower than at the start of the transient).   [10%]

Principal Assessor's comments:

A very popular question attempted by 91% of candidates. Some candidates interpreted part (a) to be asking for the meaning of the symbols in the equations rather than the terms. This alternative interpretation was accepted for marking purposes. Proofs by substitution of the result in part (c) were accepted as long as the boundary conditions were checked. Attempts at parts (c) and (d) were often undermined by carelessness in distinguishing the $\phi = \phi_0$ case (up to $t = 0$) and the $\phi = \frac{1}{2}\phi_0$ case (after $t = 0$). Poor differential equation solving techniques were again apparent.

Q3

(a)   On-line refuelling increases availability (no shutdowns for refuelling) and also increases fuel utilisation (burn-up). The main disadvantage is the increased risk of accidents as the core configuration is changed during operation. There is also no scope for in-core fuel management.

CANDU and Magnox (at the time of writing, Oldbury and Wylfa are still operating, although Oldbury is due to close later in 2012) reactors are refuelled on-line. AGRs were designed to be refuelled on-line, but in practice at not refuelled at full load (power has to be lowered when refuelling is scheduled). PWRs and BWRs are refuelled off-line, as are Fast Breeders.   [20%]

(b) For M-batch refuelling the overall reactivity given by the partial reactivity model is

$$\rho = \frac{\rho_0}{M} \sum_{i=1}^{M} \left(1 - \frac{\tau_i}{T_1} \right)$$

where τ_i is the burn-up of batch i.

In equilibrium operation $\tau_i = i T_M$ at the end of each cycle (of length T_M).

The end-of-cycle (EOC) condition is that $\rho = 0$.

$$\therefore \quad 0 = \frac{\rho_0}{M} \sum_{i=1}^{M} \left(1 - \frac{i T_M}{T_1} \right)$$

$$\therefore \quad \sum_{i=1}^{M} \frac{i T_M}{T_1} = \frac{T_M}{T_1} \sum_{i=1}^{M} i = \sum_{i=1}^{M} 1$$

$$\therefore \quad \tfrac{1}{2} M(M+1) \frac{T_M}{T_1} = M$$

$$\therefore \quad T_M = \frac{2}{M+1} T_1$$

[20%]

(c)(i) In equilibrium 3-batch operation the equilibrium cycle length $T_3 = \frac{2}{3+1} T_1 = \tfrac{1}{2} T_1$

Thus, at the end of the last cycle of 3-batch operation:

$\tfrac{1}{3}$ of the fuel has a burn-up of $\tfrac{1}{2} T_1$

$\tfrac{1}{3}$ of the fuel has a burn-up of T_1

$\tfrac{1}{3}$ of the fuel has a burn-up of $\tfrac{3}{2} T_1$

The fuel to be discharged will come from the oldest batch but $\tfrac{1}{3} - \tfrac{1}{4} = \tfrac{1}{12}$ will remain in the reactor.

Thus, at the start of the first cycle of 4-batch operation:

$\tfrac{1}{4}$ of the fuel has a burn-up of 0

$\tfrac{1}{3}$ of the fuel has a burn-up of $\tfrac{1}{2} T_1$

$\tfrac{1}{3}$ of the fuel has a burn-up of T_1

$\tfrac{1}{12}$ of the fuel has a burn-up of $\tfrac{3}{2} T_1$

Let τ_1 be the length of the first cycle of 4-batch operation. The EOC condition will then be:

$$0 = \frac{\rho_0}{4} \left(1 - \frac{\tau_1}{T_1} \right) + \frac{\rho_0}{3} \left(1 - \frac{\tau_1 + \tfrac{1}{2} T_1}{T_1} \right) + \frac{\rho_0}{3} \left(1 - \frac{\tau_1 + T_1}{T_1} \right) + \frac{\rho_0}{12} \left(1 - \frac{\tau_1 + \tfrac{3}{2} T_1}{T_1} \right)$$

$$\therefore \quad 0 = \left(\frac{1}{4} + \frac{1}{3} + \frac{1}{3} + \frac{1}{12} \right) \left(1 - \frac{\tau_1}{T_1} \right) - \frac{1}{3} \left(\frac{\tfrac{1}{2} T_1}{T_1} \right) - \frac{1}{3} \left(\frac{T_1}{T_1} \right) - \frac{1}{12} \left(\frac{\tfrac{3}{2} T_1}{T_1} \right)$$

$$\therefore \quad 0 = \left(1 - \frac{\tau_1}{T_1}\right) - \left(\frac{1}{6} + \frac{1}{3} + \frac{1}{8}\right) \quad \Rightarrow \quad \tau_1 = \frac{3}{8}T_1 \qquad [30\%]$$

(ii) At the end of the first cycle of 4-batch operation the oldest fuel (the $\frac{1}{12}$ left in the reactor at the end of the previous cycle) will be removed and the remaining $\left(\frac{1}{4} - \frac{1}{12} = \frac{1}{6}\right)$ fuel to be discharged will come from the next oldest batch.

Thus, at the start of the second cycle of 4-batch operation:

$\frac{1}{4}$ of the fuel has a burn-up of 0

$\frac{1}{4}$ of the fuel has a burn-up of $\frac{3}{8}T_1$

$\frac{1}{3}$ of the fuel has a burn-up of $\frac{1}{2}T_1 + \frac{3}{8}T_1 = \frac{7}{8}T_1$

$\frac{1}{6}$ of the fuel has a burn-up of $T_1 + \frac{3}{8}T_1 = \frac{11}{8}T_1$

Let τ_2 be the length of the second cycle of 4-batch operation. The EOC condition will be:

$$0 = \frac{\rho_0}{4}\left(1 - \frac{\tau_2}{T_1}\right) + \frac{\rho_0}{4}\left(1 - \frac{\tau_2 + \frac{3}{8}T_1}{T_1}\right) + \frac{\rho_0}{3}\left(1 - \frac{\tau_2 + \frac{7}{8}T_1}{T_1}\right) + \frac{\rho_0}{6}\left(1 - \frac{\tau_2 + \frac{11}{8}T_1}{T_1}\right)$$

$$\therefore \quad 0 = \left(\frac{1}{4} + \frac{1}{4} + \frac{1}{3} + \frac{1}{6}\right)\left(1 - \frac{\tau_2}{T_1}\right) - \frac{1}{4}\left(\frac{\frac{3}{8}T_1}{T_1}\right) - \frac{1}{3}\left(\frac{\frac{7}{8}T_1}{T_1}\right) - \frac{1}{6}\left(\frac{\frac{11}{8}T_1}{T_1}\right)$$

$$\therefore \quad 0 = \left(1 - \frac{\tau_2}{T_1}\right) - \left(\frac{3}{32} + \frac{7}{24} + \frac{11}{48}\right) \quad \Rightarrow \quad \tau_2 = \frac{37}{96}T_1 \qquad [20\%]$$

(d) In equilibrium 4-batch operation the equilibrium cycle length $T_4 = \dfrac{2}{4+1}T_1 = \frac{2}{5}T_1$

The burn-up achieved from the fuel is $B_M = MT_M$, so this change in strategy has increased the discharge burn-up by a factor of

$$\frac{4T_4}{3T_3} = \frac{4 \times \frac{2}{5}T_1}{3 \times \frac{1}{2}T_1} = 1.0667, \text{ i.e. a 6.67\% increase}$$

The main disadvantage of the change is that, because the cycle length is 20% shorter, the reactor's availability will be reduced (it will be shut down for refuelling more frequently). [10%]

Principal Assessor's comments:

A very popular question attempted by 88% of candidates. There were a large number of near-perfect answers and a large number of dreadful ones. Part (b) was done surprisingly badly given it is a standard proof. A number of candidates interpreted part (c) as meaning that 25% of each batch was to be replaced at each refuelling. The question can be interpreted in this way, but candidates who took this interpretation clearly have little understanding of the main purpose of out-of-core fuel management (to make best use of the fuel). A surprisingly large number of candidates set up the problem in part (c) correctly but then assumed that $T_3 = T_1$, rather than using the result given in part (b).

Q4

(a)   (i)   All fission reactors operate with a very sensitive neutron balance in which the number of neutrons generated per fission must equal those consumed by fission, capture and other losses. Magnox reactors use a magnesium alloy fuel cladding which has a very low neutron capture cross-section whereas AGRs use a stainless steel fuel cladding which captures more neutrons, hence the need for enrichment. AGRs also run at a much higher power density, which again requires an enriched fuel.

[10%]

(ii)   The two commercial enrichment processes use the difference in the size and mass of the U-235 and U-238 atoms in the form of uranium hexafluoride (HEX).

Both use stage-wise contacting processes in which the enrichment takes place in a number of stages, each stage giving a small change in the concentration of the U-235.

In the earlier diffusion process the separation is effected by a semi-porous membrane through which the slightly small U-235 HEX atoms are more likely to pass. Because the separation per stage is very low the process requires a large number of stages, each with its own compressor and cooler.

This process has the advantage of being relatively simple but is very expensive in energy costs.

The alternative process uses very high speed gas centrifuges in which the heavier U-238 HEX is spun to the outside of the centrifuge whilst the slightly lighter U-235 remains in the centre.

This process requires fewer stages and hence less power and space, but the construction of the centrifuges requires the use of very high grade materials to resist the enormous g forces.

Newer enrichment processes revolve round the use of specially tuned lasers which can excite (ionise) one isotope without exciting the others. The excited isotope can then be separated by an electromagnetic field. Despite much research and various claims from time to time, the commercialisation of such processes is still well into the future. It is very difficult to compete with the centrifuge process.

HEX has to be used as it is the only uranium compound which is gaseous at relatively mild conditions.

[60%]

(b)   Thermal power $P_T = \dfrac{P_E}{\eta} = \dfrac{660}{0.35} = 1885.7 \, \text{MW(th)}$

$\therefore$ Annual thermal output $O_T = 1885.7 \times 0.95 \times 365 = 65387 \, \text{MWd}$

$\therefore$ Annual fuel requirement $A = \dfrac{O_T}{B} = \dfrac{65387}{20000} = 32.69 \, \text{te}$

Increasing the enrichment will enable the burn-up of the fuel to be increased. This in turn will reduce the annual fuel requirement.

[10%]

(c)   Mass balance across the enrichment plant:

$$F = P + W$$

$$x_f F = x_p P + x_w W$$

$$\therefore \quad x_w F = x_w P + x_w W$$

$$\therefore \quad (x_f - x_w)F = (x_p - x_w)P$$

$$\therefore \quad F = \frac{(x_p - x_w)}{(x_f - x_w)} P$$

Here $P = A$ as calculated in (b)

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$$\therefore \quad F = \frac{(x_p - x_w)}{(x_f - x_w)} P = \frac{0.03 - 0.003}{0.007 - 0.003} \times 32.69 = 220.66 \text{ te}$$

$$\therefore \quad W = F - P = 220.66 - 32.69 = 187.97 \text{ te}$$

$$SWU = -W \ln x_w - P \ln x_p + F \ln x_f$$

$$\therefore \quad SWU = -187.97 \ln 0.003 - 32.69 \ln 0.03 + 220.66 \ln 0.007$$

$$\therefore \quad SWU = 111.7 \text{ te SWU} \hspace{3cm} [20\%]$$

Principal Assessor's comments:

A surprisingly unpopular question attempted by only 29% of candidates. Given that there is nothing hard about the calculations required, one can only assume that the majority of candidates had not anticipated being asked about enrichment methods and were unprepared for the question. The only common error in the quantitative parts was in part (b) where many candidates seemed to think that burn-up is defined per unit mass of the fissile fuel component, rather than, as it is, per unit mass of heavy metal.