Q1

(a)

$$\frac{1}{r^2}\frac{d}{dr}r^2\frac{d}{dr}\phi(r)+\frac{(\eta-1)\Sigma_a}{D}\phi(r)=0$$

Substitute $\phi(r)=\dfrac{1}{r}\psi(r)$

$$\therefore \quad \frac{1}{r^2}\frac{d}{dr}r^2\frac{d}{dr}\left(\frac{1}{r}\psi(r)\right)+\frac{(\eta-1)\Sigma_a}{D}\frac{1}{r}\psi(r)=0$$

$$\therefore \quad \frac{1}{r^2}\frac{d}{dr}r^2\left(\frac{1}{r}\frac{d\psi}{dr}-\frac{\psi}{r^2}\right)+\frac{(\eta-1)\Sigma_a}{D}\frac{\psi}{r}=0$$

$$\therefore \quad \frac{1}{r^2}\frac{d}{dr}\left(r\frac{d\psi}{dr}-\psi\right)+\frac{(\eta-1)\Sigma_a}{D}\frac{\psi}{r}=0$$

$$\therefore \quad \frac{1}{r^2}\left(\frac{d\psi}{dr}+r\frac{d^2\psi}{dr^2}-\frac{d\psi}{dr}\right)+\frac{(\eta-1)\Sigma_a}{D}\frac{\psi}{r}=0$$

$$\therefore \quad \frac{1}{r}\frac{d^2\psi}{dr^2}+\frac{(\eta-1)\Sigma_a}{D}\frac{\psi}{r}=0$$

$$\therefore \quad \frac{d^2\psi}{dr^2}+\frac{(\eta-1)\Sigma_a}{D}\psi=0$$

This is an SHM equation: $$\frac{d^2\psi}{dr^2}+B^2\psi=0$$

where $B^2=\dfrac{(\eta-1)\Sigma_a}{D}$ $\therefore \quad \psi=A\sin(Br)+C\cos(Br)$

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

The flux must be finite when $r=0 \quad \Rightarrow \quad C=0$

$$\therefore \quad \phi(r)=\frac{A}{r}\sin(Br)$$ [30%]

(b)

(i)   The number of uranium atoms per unit volume

$$N_U=0.05\frac{\rho}{M}L=0.05\times\frac{10970}{270}\times6.022\times10^{26}=1.223\times10^{27}\ \text{m}^{-3}$$

$$\therefore \quad N_5=0.03\times1.223\times10^{27}=3.670\times10^{25}\ \text{m}^{-3}$$

and $$N_8=0.97\times1.223\times10^{27}=1.187\times10^{27}\ \text{m}^{-3}$$

where N_5 and N_8 are the number of ^{235}U and ^{238}U atoms per unit volume.

$$\Sigma_a=\sum_i N_i\sigma_{ai}=\sum_i N_i(\sigma_{ci}+\sigma_{fi})$$

$$\therefore \quad \Sigma_a=3.670\times10^{25}(107+580)\times10^{-28}+1.187\times10^{27}(2.75+0)\times10^{-28}=2.848\ \text{m}^{-1}$$

Only the ^{235}U is fissile

$$\therefore \quad \Sigma_f = 3.670 \times 10^{25} \times 580 \times 10^{-28} = 2.129 \text{ m}^{-1}$$

$$\therefore \quad \eta = \frac{\nu \Sigma_f}{\Sigma_a} = \frac{2.43 \times 2.129}{2.848} = 1.817 \qquad [20\%]$$

(ii)   In a critical spherical reactor with negligible extrapolation distance, the flux falls to zero when

$$\sin(BR) = 0$$

with $R > 0$, i.e. $\qquad\qquad\qquad BR = \pi$

$$B^2 = \frac{(\eta - 1)\Sigma_a}{D} = \frac{(1.817 - 1) \times 2.848}{0.01} = 232.7 \text{ m}^{-2} \quad \Rightarrow \quad B = 15.25 \text{ m}^{-1}$$

$$\therefore \quad R = \frac{\pi}{B} = \frac{\pi}{15.25} = 0.206 \text{ m}$$

$$\therefore \quad V = \tfrac{4}{3}\pi R^3 = \tfrac{4}{3}\pi (0.206)^3 = 0.0366 \text{ m}^3 \qquad [15\%]$$

(c)   The maximum flux occurs at $r = 0$.

$$\phi_{max} = AB \text{ as } \underset{r \to 0}{L} \frac{A}{r}\sin(Br) = AB$$

Volume-average flux $\qquad\qquad \bar{\phi} = \dfrac{\int_0^R 4\pi r^2 \phi \, dr}{\tfrac{4}{3}\pi R^3}$

$$\therefore \quad \bar{\phi} = \frac{1}{\tfrac{4}{3}\pi R^3} \int_0^R 4\pi A r \sin(Br) \, dr$$

$$\therefore \quad \bar{\phi} = \frac{3A}{R^3} \int_0^R r \sin(Br) \, dr = \frac{3A}{R^3}\left\{ \left[-\frac{r}{B}\cos(Br) \right]_0^R + \int_0^R \frac{1}{B}\cos(Br) \, dr \right\}$$

Noting that $BR = \pi$ and therefore $\cos(BR) = -1$ and $\sin(BR) = 0$

$$\therefore \quad \bar{\phi} = = \frac{3A}{R^3}\left\{ \frac{R}{B} + \left[\frac{1}{B^2}\sin(Br) \right]_0^R \right\} = \frac{3A}{BR^2}$$

$$\therefore \quad F = \frac{\phi_{max}}{\bar{\phi}} = AB \div \frac{3A}{BR^2} = \tfrac{1}{3}B^2 R^2 = \tfrac{1}{3}\pi^2 \qquad [25\%]$$

(d)   Form factors can be improved (reduced) by:

- Use of a reflector
- Varying the enrichment of the fuel – lower enrichment towards the middle of the core
- Use of burnable poisons to suppress the flux in the middle of the reactor
- Use of control rods to shape the flux   [10%]

Assessor's comments:

An extremely popular question attempted by 97% of candidates, and done well by many of them. However, there were also a fair number of recurring errors:

Incorrect boundary conditions and/or arguments were used to eliminate the cosine term in the general solution in (a).

Demonstrations that the quoted solution in (a) was a solution by substitution into the diffusion equation were accepted but only got full credit if there was a valid discussion of the prevailing boundary conditions.

The significance of only 5% of the core being occupied by fuel eluded many.

A surprising number of candidates calculated the value of η for natural uranium fuel rather than 3% enriched uranium.

Several candidates commented on how small the minimum volume core was, not appreciating that a reactor that small would instantly become subcritical and that in practice the core would be substantially larger.

Implausible reactor volumes (both large and small) were calculated without comment by several candidates.

The integral to find the volume-average flux was set up incorrectly all too often. In particular, many failed to recognise that spherical symmetry meant $dV = 4\pi r^2 dr$.

The limiting value of $\dfrac{\sin(Br)}{r}$ as $r \rightarrow 0$ was got wrong by many.

A surprisingly large number of candidates did not know the locations of the zeroes of $\sin(\theta)$.

Similarly, several candidates did not recognise that the maximum flux would occur at core centre.

Q2

(a)   In steady state
$$\frac{dI}{dt} = \gamma_i \Sigma_f \phi - \lambda_i I = 0 \quad \Rightarrow \quad I_0 = \frac{\gamma_i \Sigma_f \phi}{\lambda_i}$$

$$\frac{dX}{dt} = \gamma_x \Sigma_f \phi + \lambda_i I - \lambda_x X - \sigma X \phi = 0 \quad \Rightarrow \quad X_0 = \frac{\gamma_x \Sigma_f \phi + \lambda_i I_0}{\lambda_x + \sigma \phi}$$

$$\therefore \quad X_0 = \frac{\gamma_x \Sigma_f \phi + \gamma_i \Sigma_f \phi}{\lambda_x + \sigma \phi} = \frac{(\gamma_x + \gamma_i)\Sigma_f \phi}{\lambda_x + \sigma \phi}$$

For a high power reactor the flux ϕ is high, so $\sigma \phi \gg \lambda_x$ and therefore

$$X_0 \rightarrow \frac{(\gamma_x + \gamma_i)\Sigma_f}{\sigma}$$

The reactivity loss (poisoning) $\rho = -\dfrac{\sigma X}{\nu \Sigma_f}$

$$\therefore \quad \rho_{Xe0} = -\frac{\sigma X_0}{\nu \Sigma_f} \rightarrow -\frac{(\gamma_x + \gamma_i)\Sigma_f}{\nu \Sigma_f} = -\frac{(\gamma_x + \gamma_i)}{\nu} \qquad\qquad [20\%]$$

(b) $X_0 = \dfrac{(\gamma_x + \gamma_i)\Sigma_f \phi}{\lambda_x + \sigma \phi} = \dfrac{(0.003 + 0.061)\times 10^{18}}{2.093\times 10^{-5} + 2.75\times 10^{-22}\times 10^{18}}\Sigma_f = 2.163\times 10^{20}\Sigma_f$

$$\therefore \quad \rho_{Xe0} = -\frac{\sigma X_0}{\nu \Sigma_f} = \frac{2.75\times 10^{-22}\times 2.163\times 10^{20}\Sigma_f}{2.43\Sigma_f} = -0.0245$$

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The limiting value from (a) $= -\dfrac{(\gamma_x + \gamma_i)}{\nu} = -\dfrac{(0.003 + 0.061)}{2.43} = -0.0263$

So ρ_{Xe0} is 93% of this limiting value. Importantly the approximate result is conservative (overestimating the poisoning effect).   [15%]

(c)   After shutdown $\phi = 0$, so $\qquad\qquad \dfrac{dI}{dt} = -\lambda_i I$ $\qquad\qquad$ (1)

$$\frac{dX}{dt} = \lambda_i I - \lambda_x X \quad \Rightarrow \quad \frac{dX}{dt} + \lambda_x X = \lambda_i I \qquad\qquad (2)$$

At $t = 0$, $I = I_0$ and $X = X_0$ if shut down is from steady state.

The solution of (1) is, by inspection:

$$I = I_0 \exp(-\lambda_i t)$$

For (2), the complementary function is, by inspection:

$$X_{\mathrm{CF}} = A \exp(-\lambda_x t)$$

The particular integral is, by inspection, of the form:

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

$$\therefore \quad -\lambda_i B \exp(-\lambda_i t) + \lambda_x B \exp(-\lambda_i t) = \lambda_i I_0 \exp(-\lambda_i t)$$

$$\therefore \quad B = \frac{\lambda_i I_0}{\lambda_x - \lambda_i}$$

Thus the general solution is

$$X = X_{\mathrm{CF}} + X_{\mathrm{PI}} = A \exp(-\lambda_x t) + \frac{\lambda_i I_0}{\lambda_x - \lambda_i} \exp(-\lambda_i t)$$

The boundary condition is: $X = X_0$ at $t = 0$:

$$\therefore \quad X_0 = A + \frac{\lambda_i I_0}{\lambda_x - \lambda_i} \quad \Rightarrow \quad A = X_0 - \frac{\lambda_i I_0}{\lambda_x - \lambda_i}$$

$$\therefore \quad X = \left[X_0 - \frac{\lambda_i I_0}{\lambda_x - \lambda_i} \right] \exp(-\lambda_x t) + \frac{\lambda_i I_0}{\lambda_x - \lambda_i} \exp(-\lambda_i t)$$

Using the data given and the results in (b) above

$$I_0 = \frac{\gamma_i \Sigma_f \phi}{\lambda_i} = \frac{0.061 \times 10^{18}}{2.874 \times 10^{-5}} \Sigma_f = 2.122 \times 10^{21} \Sigma_f$$

$$X_0 = 2.163 \times 10^{20} \Sigma_f$$

$$\frac{\lambda_i I_0}{\lambda_x - \lambda_i} = \frac{2.874 \times 10^{-5}}{2.093 \times 10^{-5} - 2.874 \times 10^{-5}} \times 2.122 \times 10^{21} \Sigma_f = -7.809 \times 10^{21} \Sigma_f$$

Thus, after 2 hours (7200 s)

$$X = \left[2.163 \times 10^{20} \Sigma_f + 7.809 \times 10^{21} \Sigma_f \right] \exp(-2.093 \times 10^{-5} \times 7200)$$

$$-7.809 \times 10^{21} \Sigma_f \exp(-2.874 \times 10^{-5} \times 7200)$$

$$\therefore \quad X = 5.531 \times 10^{20} \, \Sigma_f$$

The poisoning to be overcome is therefore

$$\rho_{Xe} = -\frac{\sigma X}{v \Sigma_f} = \frac{2.75 \times 10^{-22} \times 5.531 \times 10^{20} \, \Sigma_f}{2.43 \Sigma_f} = -0.0626$$

A substantial increase above the steady-state poisoning level.   [50%]

(d)   The reactor will only continue to operate if the xenon population is not increasing.

After restart, the governing equation is

$$\frac{dX}{dt} = \gamma_x \Sigma_f \phi + \lambda_i I - \lambda_x X - \sigma X \phi$$

but the initial flux will be negligible, so the rate of change of the xenon population after restart is (to a good approximation)

$$\frac{dX}{dt} = \lambda_i I - \lambda_x X$$

At restart $I = I_0 \exp(-\lambda_i t)$

$$\therefore \quad I = 2.122 \times 10^{21} \, \Sigma_f \, \exp(-2.874 \times 10^{-5} \times 7200) = 1.725 \times 10^{21} \, \Sigma_f$$

$$\frac{dX}{dt} = 2.874 \times 10^{-5} \times 1.725 \times 10^{21} \, \Sigma_f - 2.093 \times 10^{-5} \times 5.531 \times 10^{20} \, \Sigma_f$$

$$\therefore \quad \frac{dX}{dt} = 3.800 \times 10^{16} \, \Sigma_f$$

As this is > 0, the xenon population will continue to rise, and therefore the excess reactivity available will <u>not</u> be sufficient to maintain criticality.   [15%]

Assessor's comments:

Another very popular question attempted by 85% of candidates, and done well by many of them. Common errors included:

Candidates thinking that the complementary function for the ODE governing the xenon population post shutdown would be $X_0 \exp(-\lambda_x t)$ rather than $A \exp(-\lambda_x t)$.

Candidates setting $\phi = 0$ in only one of the two equations for the iodine/xenon populations post shutdown.

The substitution of numerical values and calculations arising therefrom were both done surprisingly badly. There was confusion between the values for yields (γ) and decay constants (λ), and confusion between values of λ_x and λ_i.

Another common error was in the failure to convert barns to m^2.

Many candidates did not show enough detail of their numerical calculations to enable the assessor to identify where they had gone wrong and thus lost the opportunity for partial credit.

Q3

(a)   In equilibrium operation the end-of-cycle condition is

$$\sum_{i=1}^{M} \frac{1}{M}\rho_0\left(1-\frac{i\mu}{T}\right)=0$$

where μ is the equilibrium cycle length.

$$\therefore \quad \sum_{i=1}^{M}1-\sum_{i=1}^{M}\frac{i\mu}{T}=\sum_{i=1}^{M}1-\frac{\mu}{T}\sum_{i=1}^{M}i=0$$

$$\therefore \quad M-\frac{\mu}{T}\frac{1}{2}M(M+1)=0$$

$$\therefore \quad \mu=\frac{2T}{M+1}$$

The burnup accumulated by each batch (which resides in the reactor for M cycles) is therefore

$$B=M\alpha\mu=\frac{2\alpha MT}{M+1} \qquad\qquad (1)\qquad\qquad [20\%]$$

(b) $$A=\frac{\mu}{\mu+\Delta}=\frac{2T/(M+1)}{[2T/(M+1)]+\Delta}=\frac{2T}{2T+(M+1)\Delta} \qquad (2)\qquad [10\%]$$

(c)   Looking at equation (1), B increases monotonically with increasing M. So it is maximised as $M\to\infty$. M can, in principle be as large as the number of fuel assemblies in the core (~200 for a typical PWR).

$$\therefore \quad B_{\text{max}}\approx 2\alpha T$$

Looking at equation (2), A increases as M decreases. The smallest value M can take is 1.

$$\therefore \quad A_{\text{max}}=\frac{2T}{2T+2\Delta}=\frac{T}{T+\Delta}$$

These competing effects make the simultaneous maximisation of B and A impossible.   [15%]

(d) $$f=\frac{3A}{A_{\text{max}}}+\frac{B}{B_{\text{max}}}$$

$$\therefore \quad f=\frac{3\times 2T}{2T+(M+1)\Delta}\times\frac{T+\Delta}{T}+\frac{2\alpha MT}{M+1}\times\frac{1}{2\alpha T}$$

$$\therefore \quad f=\frac{6(T+\Delta)}{2T+(M+1)\Delta}+\frac{M}{M+1}$$

f is maximised when $\dfrac{df}{dM}=0$.

$$\therefore \quad \frac{df}{dM}=-\frac{6\Delta(T+\Delta)}{[2T+(M+1)\Delta]^2}+\frac{1}{M+1}-\frac{M}{(M+1)^2}=0$$

$$\therefore \quad \frac{df}{dM}=-\frac{6\Delta(T+\Delta)}{[2T+(M+1)\Delta]^2}+\frac{1}{(M+1)^2}=0$$

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$$\therefore \quad [2T+(M+1)\Delta]^2 = 6\Delta(T+\Delta)(M+1)^2$$

$$\therefore \quad 2T+(M+1)\Delta = \sqrt{6\Delta(T+\Delta)}(M+1)$$

$$\therefore \quad (M+1)\left[\sqrt{6\Delta(T+\Delta)}-\Delta\right] = 2T$$

$$\therefore \quad M = \frac{2T}{\sqrt{6\Delta(T+\Delta)}-\Delta}-1$$

So substituting the specified values of T and Δ:

$$\therefore \quad M = \frac{2\times135}{\sqrt{6\times4(135+4)}-4}-1 = 4.022, \text{ i.e. } 4$$

4-batch operation is optimal.   [30%]

(e)   The total cycle length $= \mu+\Delta$

$$\mu = \frac{2T}{M+1} = \frac{2\times135}{4+1} = 54 \text{ weeks}$$

$$\mu+\Delta = 54+4 = 58 \text{ weeks}$$

This is close to (but not equal to a year). From both operational and economic perspectives, it would be preferable to have an annual cycle, so that outages could be scheduled at the same time each year (coinciding with the lowest demand period, when electricity prices are lowest).

This can be achieved by reducing T appropriately (so that $\mu = 48$ weeks, i.e. $T = 120$ weeks) by decreasing the enrichment of the fuel slightly.

For this value of T the optimal value of M is

$$\therefore \quad M = \frac{2\times120}{\sqrt{6\times4(120+4)}-4}-1 = 3.748$$

So 4-batch operation is still optimal.   [25%]

Assessor's comments:

The least popular question attempted by 52% of candidates.

A somewhat non-standard fuel management question that clearly deterred some candidates. There were nevertheless many good attempts.

Attempts to find the optimal batch refuelling scheme in (d) were rather often undermined by poor algebra in rearranging the equations and poor differentiation skills. Some candidates found the optimal batch size by exhaustive enumeration. This was accepted and full credit was given if full working was provided.

Most of the discussion of part (e) was rather superficial given proportion of marks available.

Q4

(a)   Reprocessing starts with the shearing of the fuel pins to release the spent fuel which is then dissolved in hot concentrated nitric acid. Virtually all the spent fuel is dissolved in this process. The solution is then clarified by centrifugation and passed to the first extraction column. Here it is contacted with a solvent [tri-butyl phosphate dissolved in odourless kerosene (TBP/OK)] and the plutonium and uranium pass into the solvent phase leaving the fission products in the aqueous phase. The two phases separate and the fission products go to evaporation, vitrification and long-term storage. The organic phase containing the Pu and U is then treated with a reducing agent which reduces the valency of the Pu. This renders the Pu soluble in dilute nitric acid, so the organic stream is now mixed with dilute nitric acid in a second contactor and the Pu is separated off in the aqueous stream leaving the U still in the organic stream. The U is finally recovered from the organic stream by backwashing with very slightly acidified water.

Both Pu and U are further purified using TBP/OK washing and backwashing, the Pu and U are usually finally recovered as oxides.

Waste arises at all stages of the process. The remains of the fuel pins are encapsulated in cement, the dissolver off-gas is scrubbed to remove nitrous fumes, iodine and ^{14}C. Some krypton is discharged to the atmosphere. The fission product stream usually referred to as highly active liquor (HAL) is the most dangerous of all the waste arising but its volume is very small. It is evaporated to reduce volume, then encapsulated in a glass matrix (vitrification) and placed in stainless steel containers for long-term storage.

Wastes also arise from the purification of the U and Pu products. These are referred to as medium active liquors (MAL). They are also evaporated and mixed with the HAL for vitrification. Low active waste streams arising from a number of sources are subject to chemical treatment before discharge to the environment. There are also a number of low level solid wastes arising which go to the controlled landfill.   [30%]

(b)

(i)   The past decisions by the UK and France to reprocess PWR and AGR fuels were taken at a time of great energy shortage. The plan at that time was to recover the Pu to fuel fast breeder reactors (FBRs) and also to use the recovered U as a breeding blanket. The only real use for the recovered Pu at present is in the form of mixed oxide fuel (MOX), and with increasing energy prices reprocessing could again become attractive.

The main downside of reprocessing is that, although it does separate the various wastes, it results in an overall increase in waste volume and there are some discharges to the environment. There is also the associated proliferation risk and the question of what to do with the recovered Pu, although, in practice, it is of little use for weapons as it is largely ^{240}Pu and ^{241}Pu, whereas weapons grade material is largely ^{239}Pu. Thus, whilst reprocessing is not really financially viable at the moment, it is quite likely that it will be in the not-too-distant future.   [10%]

(ii)   Reprocessing is essential for the old style Magnox fuel because it is not suitable for long-term storage. PWR and AGR fuel <u>can</u> be stored safely but there are still political problems finding suitable sites.   [5%]

(iii) The recovered plutonium could be used as MOX or perhaps in FBRs. It is not useable in nuclear weapons [see (i)].   [5%]

(c)
$$F = P + W$$
$$x_F F = x_P P + x_W W$$
$$\therefore \quad F = 100 + W \quad\quad (1)$$

and
$$0.007F = 0.04 \times 100 + 0.003W$$
$$\therefore \quad 0.007F = 4 + 0.003W \quad\quad (2)$$

0.003×(1):
$$0.003F = 0.3 + 0.003W \quad\quad (3)$$

(2) − (3):
$$0.004F = 3.7$$
$$\therefore \quad F = 925 \text{ tonnes}$$

$$\therefore \quad W = F - P = 925 - 100 = 825 \text{ tonnes}$$

Separative work:
$$SWU = P(-\ln x_P) + W(-\ln x_W) - F(-\ln x_F)$$
$$\therefore \quad SWU = 100(-\ln 0.04) + 825(-\ln 0.003) - 925(-\ln 0.007)$$
$$\therefore \quad SWU = 321.89 + 4792.54 - 4589.71 = 524.72 \text{ tonnes SWU} \quad\quad [15\%]$$

(d) Mass of recovered uranium $M_R = 96$ tonnes

1% reprocessing loss = 0.96 tonnes

$\therefore$ Mass of uranium available $F_R = 95.04$ tonnes

Mass balance on recovered uranium:
$$F_R = P_R + W_R$$
$$x_{FR} F_R = x_{PR} P_R + x_{WR} W_R$$
$$\therefore \quad 95.04 = P_R + W_R \quad\quad (4)$$

and
$$0.008 \times 95.04 = 0.04 P_R + 0.003 W_R$$
$$\therefore \quad 0.76032 = 0.04 P_R + 0.003 W_R \quad\quad (5)$$

0.003×(4):
$$0.003 \times 95.04 = 0.003 P_R + 0.003 W_R$$
$$\therefore \quad 0.28512 = 0.003 P_R + 0.003 W_R \quad\quad (6)$$

(5) − (6):
$$0.4752 = 0.037 P_R$$
$$\therefore \quad P_R = 12.84 \text{ tonnes}$$

$$\therefore \quad W_R = F_R - P_R = 95.04 - 12.84 = 82.20 \text{ tonnes}$$

Product from fresh feed:
$$P' = P - P_R = 100 - 12.84 = 87.16 \text{ tonnes}$$

Amount of fresh feed:
$$F' = F \times \frac{P'}{P} = 925 \times \frac{87.16}{100} = 806.23 \text{ tonnes}$$

Saving of feed:
$$\Delta F = F - F' = 925 - 806.23 = 118.77 \text{ tonnes}$$

Separative work for reprocessed feed:

$$SWU_R = P_R(-\ln x_{PR}) + W_R(-\ln x_{WR}) - F_R(-\ln x_{FR})$$

$$\therefore \quad SWU_R = 12.84(-\ln 0.04) + 82.20(-\ln 0.003) - 95.04(-\ln 0.008)$$

$$\therefore \quad SWU_R = 41.33 + 477.51 - 458.88 = 59.96 \text{ tonnes SWU}$$

SWU for fresh feed:

$$SWU' = SWU \times \frac{P'}{P} = 524.72 \times \frac{87.16}{100} = 457.35 \text{ tonnes SWU}$$

Saving of SWU:

$$\Delta SWU = SWU - SWU' - SWU_R = 524.72 - 457.35 - 59.96 = 7.41 \text{ tonnes SWU} \qquad [25\%]$$

(e) (A) Cost saving from reduction in feed $= c_F \Delta F = 70 \times 118.77 \times 10^3 = \$8,313,900$

(B) Cost saving from reduction in SWU $= c_{SWU} \Delta SWU = 100 \times 7.41 \times 10^3 = \$741,000$

(C) Cost of reprocessing $= c_R M_R = 1000 \times 96 \times 10^3 = \$96,000,000$

(D) Alternative cost of disposal of spent fuel $= c_D M_R = 400 \times 96 \times 10^3 = \$38,400,000$

So, the net additional cost of reprocessing is:

$C - A - B - D = \$96,000,000 - \$8,313,900 - \$741,000 - \$38,400,000 = \$48,545,100$

Reprocessing is clearly uneconomic at current prices. [10%]

Assessor's comments:

A question attempted by 67% of candidates.
The descriptive parts [(a) and (b)] were generally well done by those able to distinguish between waste processing and spent fuel reprocessing.
Part (c) was done correctly by the vast majority of candidates.
Part (d) was done less well. Many candidates evidently had a good idea of the calculations required but confusion over which stream was feed/product in the reprocessing mass balance calculations undermined many attempts.
In the cost calculation in (e) many made the incorrect assumption that enrichment plant tails would accrue spent fuel waste disposal costs.