The University of Nottingham

DEPARTMENT OF MECHANICAL, MATERIALS AND MANUFACTURING ENGINEERING

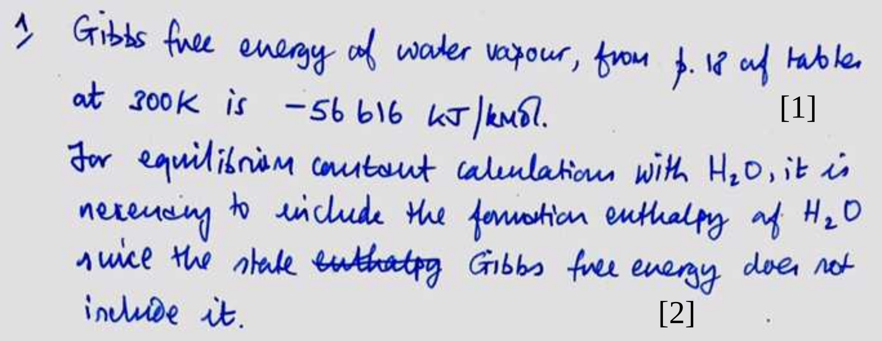
A LEVEL 4 MODULE, SPRING SEMESTER 2016-2017

ADVANCED THERMAL POWER SYSTEMS

Time allowed ONE Hour and THIRTY Minutes

SECTION A

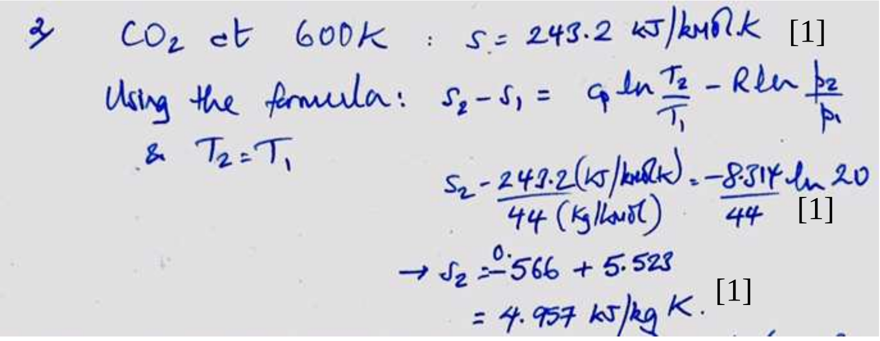
1. State from the tables the value of Gibbs free energy for water vapour at 300K. In calculating the Equilibrium constant for reactions with water, what further consideration is required for the Gibbs free energy?



1/ Gibbs free energy of water vapour, from p. 18 of table at 300K is $-56\,616$ kJ/kmol. [1]

For equilibrium constant calculations with H_2O, it is necessary to include the formation enthalpy of H_2O since the state ~~enthalpy~~ Gibbs free energy does not include it. [2]

2. Calculate the specific entropy of carbon dioxide at 600K and 20 bar.



2/ CO_2 at 600K : $s = 243.2$ kJ/kmol K [1]

Using the formula: $s_2 - s_1 = c_p \ln \frac{T_2}{T_1} - R \ln \frac{p_2}{p_1}$

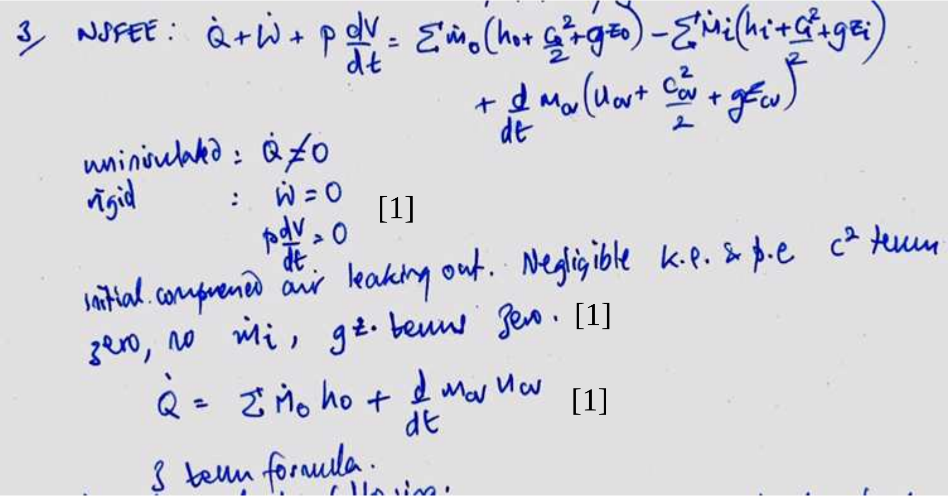
& $T_2 = T_1$

$$s_2 - \frac{243.2\,(\text{kJ/kmol K})}{44\,(\text{kg/kmol})} = -\frac{8.314}{44} \ln 20 \quad [1]$$

$$\rightarrow s_2 = -0.566 + 5.523$$

$$= 4.957 \text{ kJ/kg K.} \quad [1]$$

3. Demonstrate how the non-steady-flow energy equation can be reduced to an exact 3 term formula for an uninsulated, rigid tank of compressed air discharging slowly to the atmosphere, in which kinetic and potential effects are negligible.



3/ NSFEE: $\dot{Q} + \dot{W} + p\frac{dV}{dt} = \sum \dot{m}_o\left(h_o + \frac{c_o^2}{2} + gz_o\right) - \sum \dot{m}_i\left(h_i + \frac{c_i^2}{2} + gz_i\right)$

$$+ \frac{d}{dt} m_{cv}\left(u_{cv} + \frac{c_{cv}^2}{2} + gz_{cv}\right)$$

uninsulated : $\dot{Q} \neq 0$

rigid : $\dot{W} = 0$ [1]

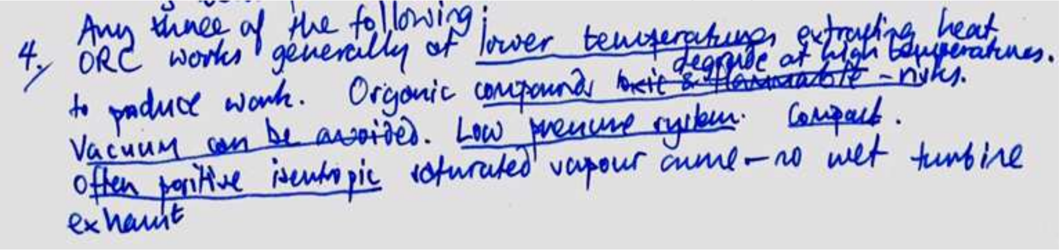
$p\frac{dV}{dt} = 0$

initial compressed air leaking out. Negligible k.e. & p.e c^2 term zero, no $\dot{m}_i$, gz term zero. [1]

$$\dot{Q} = \sum \dot{m}_o h_o + \frac{d}{dt} m_{cv} u_{cv} \quad [1]$$

3 term formula.

4. Briefly describe three implications of using organic Rankine cycles.

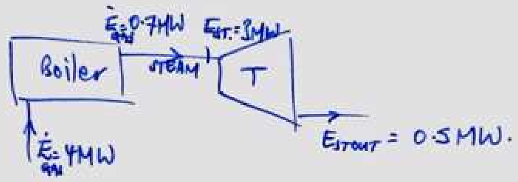


4/ Any three of the following:

ORC works generally at lower temperatures, extracting heat to produce work. Organic compounds ~~toxic & flammable~~ degrade at high temperatures - risks. Vacuum can be avoided. Low pressure system. Compact. often positive isentropic saturated vapour curve – no wet turbine exhaust

5. A boiler is fired by hot gases with an ingoing flow exergy of 4MW and exhaust exergy of 0.7MW. It powers a steam turbine which receives steam with flow exergy going in of 3MW and the steam finally condenses, going out with flow exergy of 0.5MW. Calculate the irreversibility of the boiler.

5



Irreversibility of the boiler:

$\dot{I} =$ Exergy in − Exergy out

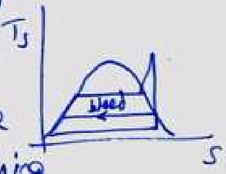
[1] [1]

$= (4 - 0.7) - (3 - 0.5)$

$= 3.3 - 2.5 = \underline{\cancel{0.2}\,0.8\text{ MW}}.$ [1]

6. Briefly describe the benefits of feed heating in a Rankine cycle, and further, the implications of using feed heating in a heat recovery steam generator application.

6 Benefits of feed heating:

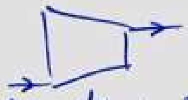


The bleed steam at intermediate pressure raises the temperature of water prior to reaching [1] the economiser. This means average heat addition temperature is raised from the heat source. ∴ higher efficiency. [1]

In HRSG, the feed heating is generally redundant since the higher exhaust temperature cannot be used. Except in case of molten salt systems where high exhaust of molten salt is desired. [1]

7. For a centrifugal gas compressor with isentropic efficiency of 90% at a pressure ratio of 8, calculate the polytropic efficiency for air with γ = 1.4.

7



$r_p = 8$ $\eta_{isen} = 90\%$

Use formula: $\eta_i = \dfrac{r_p^{\frac{\gamma-1}{\gamma}} - 1}{r_p^{\frac{\gamma-1}{\gamma\eta_{poc}}} - 1} \Rightarrow 0.9 = \dfrac{8^{\frac{0.4}{1.4}} - 1}{8^{\frac{0.4}{1.4\eta_{poc}}} - 1}$ [1]

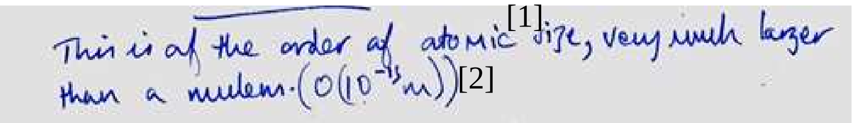
$8^{\frac{0.4}{1.4\eta_{poc}}} = 1.902$

$\frac{0.4}{1.4\eta_{poc}} \ln 8 = \ln 1.902 \rightarrow$ [1] $\eta_{poc} = \frac{\ln 8}{\ln 1.902} \times 0.286 = \underline{0.924.}$ [1]

8. Briefly describe the function of moderation in nuclear power generation.

8 Moderation slows fast neutrons to thermal speeds, [2] so that they can cause fission with fissile uranium. [1]

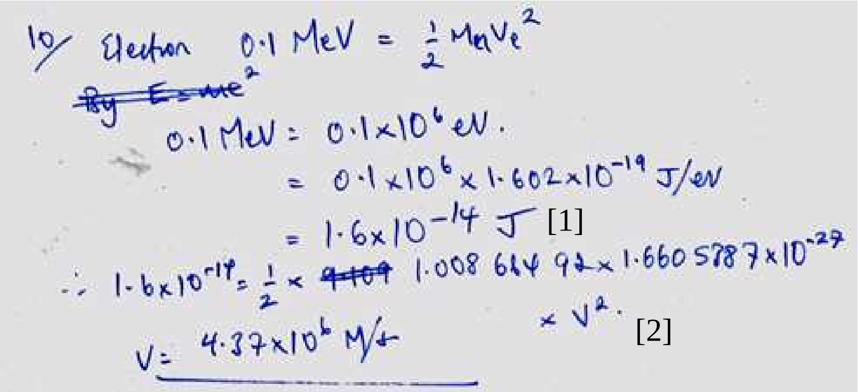
9. A typical thermal neutron has a deBroglie wavelength in the order of 10^{-10}m. Comment on the order of magnitude.



[1]

This is of the order of atomic size, very much larger than a nucleus. ($O(10^{-15} m)$) [2]

10. Calculate the speed of a neutron with a kinetic energy of 0.1 MeV.



10/ Electron 0.1 MeV $= \frac{1}{2} M_a V_e^2$

~~By $E = mc^2$~~

0.1 MeV $= 0.1 \times 10^6$ eV.

$= 0.1 \times 10^6 \times 1.602 \times 10^{-19}$ J/eV

$= 1.6 \times 10^{-14}$ J [1]

$\therefore 1.6 \times 10^{-14} = \frac{1}{2} \times$ ~~9.109~~ $1.008\,664\,92 \times 1.660\,5787 \times 10^{-27} \times V^2$. [2]

$V = \underline{4.37 \times 10^6 \text{ m/s}}$

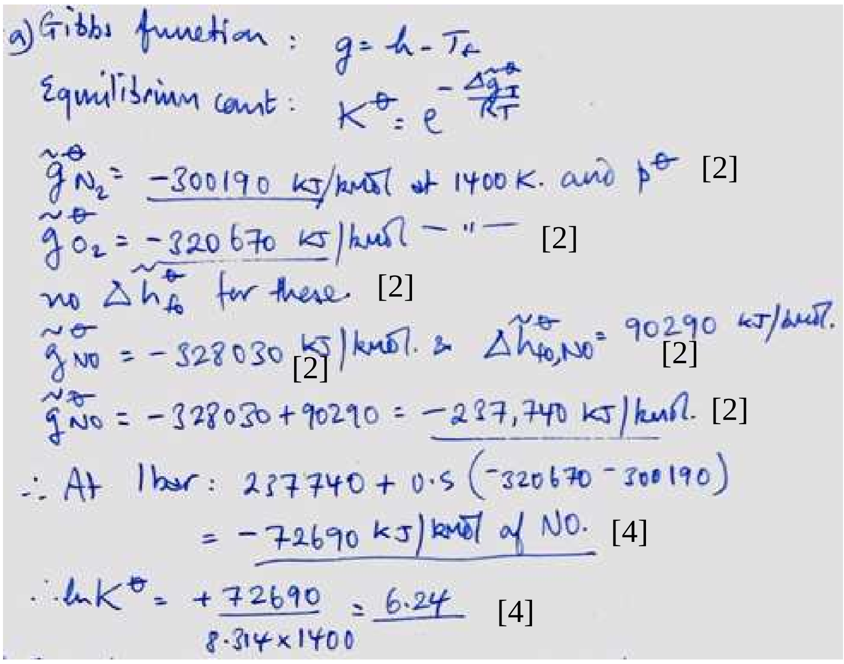
SECTION B

ANSWER TWO OUT OF FOUR QUESTIONS IN THIS SECTION

11. By determining Gibbs function from entropy and enthalpy, calculate the equilibrium constant for the following reaction at 1400K:

$$\frac{1}{2}N_2 + \frac{1}{2}O_2 \leftrightarrow NO$$

[20 marks]



a) Gibbs function : $g = h - Ts$

Equilibrium const : $K^{\ominus} = e^{-\frac{\Delta \tilde{g}_T^{\ominus}}{RT}}$

$\tilde{g}^{\ominus}_{N_2} = \underline{-300190 \text{ kJ/kmol}}$ at 1400 K. and $p^{\ominus}$ [2]

$\tilde{g}^{\ominus}_{O_2} = \underline{-320670 \text{ kJ}}$/kmol — " — [2]

no $\Delta \tilde{h}^{\ominus}_{f0}$ for these. [2]

$\tilde{g}^{\ominus}_{NO} = -328030$ [2] kJ/kmol. & $\Delta \tilde{h}^{\ominus}_{f0,NO} = 90290$ kJ/kmol. [2]

$\tilde{g}^{\ominus}_{NO} = -328030 + 90290 = \underline{-237,740 \text{ kJ/kmol}}$. [2]

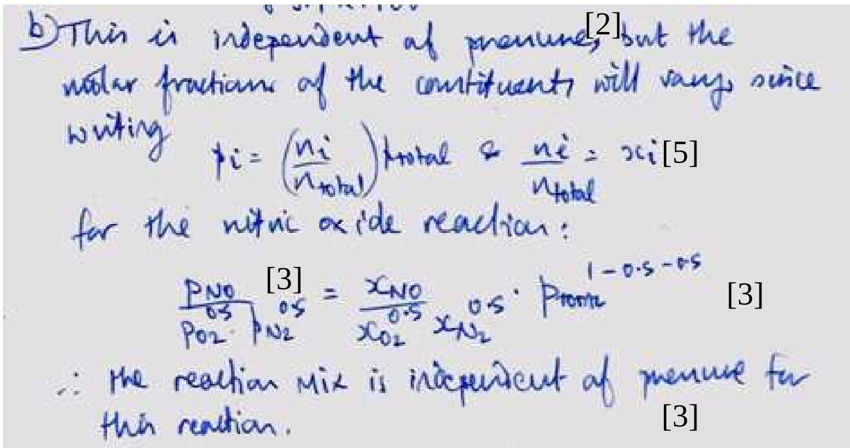
∴ At 1bar : $237740 + 0.5\,(-320670 - 300190)$

$= \underline{-72690 \text{ kJ/kmol of NO.}}$ [4]

∴ $\ln K^{\ominus} = +\dfrac{72690}{8.314 \times 1400} = \underline{6.24}$ [4]

State the effect on equilibrium constant of altering the system pressure, and describe the influence on mixture composition.

[15 marks]



b) This is independent of pressure, [2] but the molar fractions of the constituents will vary, since writing

$p_i = \left(\dfrac{n_i}{n_{total}}\right) p_{total}$ & $\dfrac{n_i}{n_{total}} = x_i$ [5]

for the nitric oxide reaction:

$$\frac{p_{NO}}{p_{O_2}^{0.5}\, p_{N_2}^{0.5}} [3] = \frac{x_{NO}}{x_{O_2}^{0.5}\, x_{N_2}^{0.5}} \cdot p_{total}^{1-0.5-0.5} \quad [3]$$

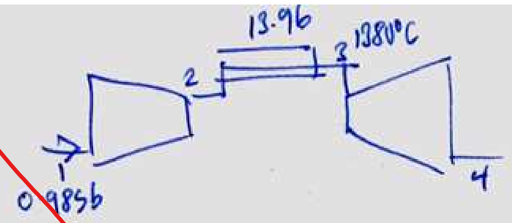
∴ the reaction mix is independent of pressure for this reaction. [3]

12. A gas turbine operates in an environment in ambient conditions -2°C and 985 mbar. The combustion chamber is at an average of 13.9 bar and the turbine inlet temperature is 1380°C. The turbine isentropic efficiency of compressor and turbine are both 88% and the mean specific heat capacity and adiabatic index are 1.004 kJ/kgK and 1.4 in the compressor and 1.254 kJ/kgK and 1.297 in the turbine.

(a) Calculate the compressor and turbine outlet temperatures.

[10]

12/



-2°C

$\eta_i = 0.88$

$\gamma = 1.4$

$C_p = 1.004$ kJ/kgK

$\eta_i = 0.88$

$\gamma = 1.297$

$C_p = 1.254$ kJ/kgK

a) compressor, isentropic:

$$T_2 = 271\left(\frac{13.96}{0.985}\right)^{0.4/1.4} = 578\,K. \quad [3]$$

$$\text{Isentropic } \eta_i : \frac{\Delta h'}{\Delta h} = \frac{578-271}{T_2-271} \rightarrow T_2 = \underline{619.9\,K.} \quad [2]$$

Turbine:

$$T_4 = (1380+273)\left(\frac{13.96}{0.985}\right)^{-\frac{0.4}{1.4}} = 775.0\,K \quad [3]$$

$$\text{Isentropic } \eta_i = \frac{\Delta h}{\Delta h'} = \frac{1653-T_4}{1653-775} \rightarrow T_4 = \underline{880.4\,K} \quad [2]$$

(b) Deter~~mine the cycle efficiency~~.

[15]

b)

$$\eta_{cycle} = \frac{W_{net}}{Q}$$

$$= \frac{(T_3-T_4)-(T_2-T_1)}{(T_3-T_2)} = \frac{(1653-775)\,[5] - (619.9-271)\,[5]}{(1653-619.9)}\,[3]$$

$$= \frac{878-348.9}{1033.1}$$

$$= \underline{0.512} \quad [5]$$

(c) What thermal management approaches might be taken to improve work output or efficiency?

[10]

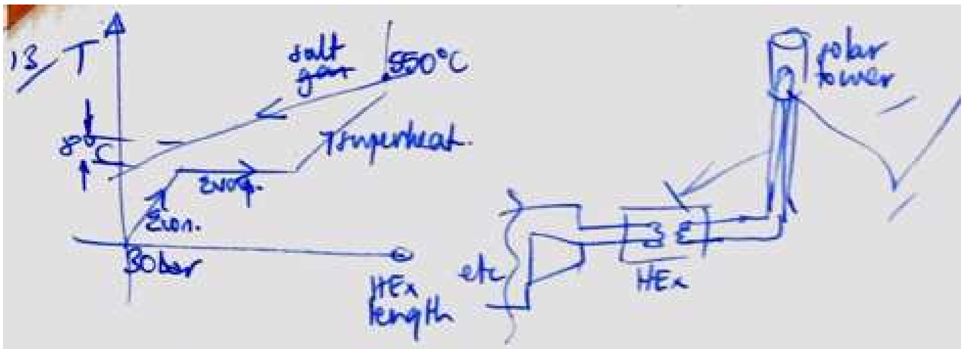
c) Heat exchangers:

- Intercooling - reduce compressor work [2]
- Recuperate – take thermal energy of exhaust to heat compressor out ∴ reducing Q required, η ↑ [2]
- Reheat – burn more fuel to get more work [3]
- ~~Improve~~ Increase allowable T_3. [3]

13. A solar thermal tower power plant uses a molten salt (c_p = 3.2 kJ/kgK and mass flow rate 22.7kg/s) to transfer heat from the solar tower to the steam cycle in a heat recovery steam generator. The salt temperature at inlet to the heat exchanger is 550°C. The steam cycle attached to the HRSG operates at 30 bar. The pinch temperature difference is 8°C and the approach temperature difference is 70°C.

    (a) Calculate the mass flow rate of steam in the cycle.

    [18]



a) Mass flow rate & SH temp = 480°C

$\dot{m}_{SALT} \cdot c_{p\,SALT} \Delta T_{SALT} = \dot{m}_{STEAM} \Delta h$ [3]

between pinch and SH.

30 bar, T_{SAT} = 233.8°C

∴ salt at economiser is 233.8 + 8 = 241.8°C. [3]

Energy lost by salt:

$22.7 \times 3.2 \times (550 - 241.8) = \underline{22.387 \text{ MW}}$. [3]

Energy gained by steam:

$\dot{m}_s (h_{480°C} - h_{SAT}) = 22.387 \times 10^3$. [3]

[6]

$\dot{m}_s = \frac{22.387 \times 10^3}{(3411 - 1008)} = \underline{9.32 \text{ kg/s}}$

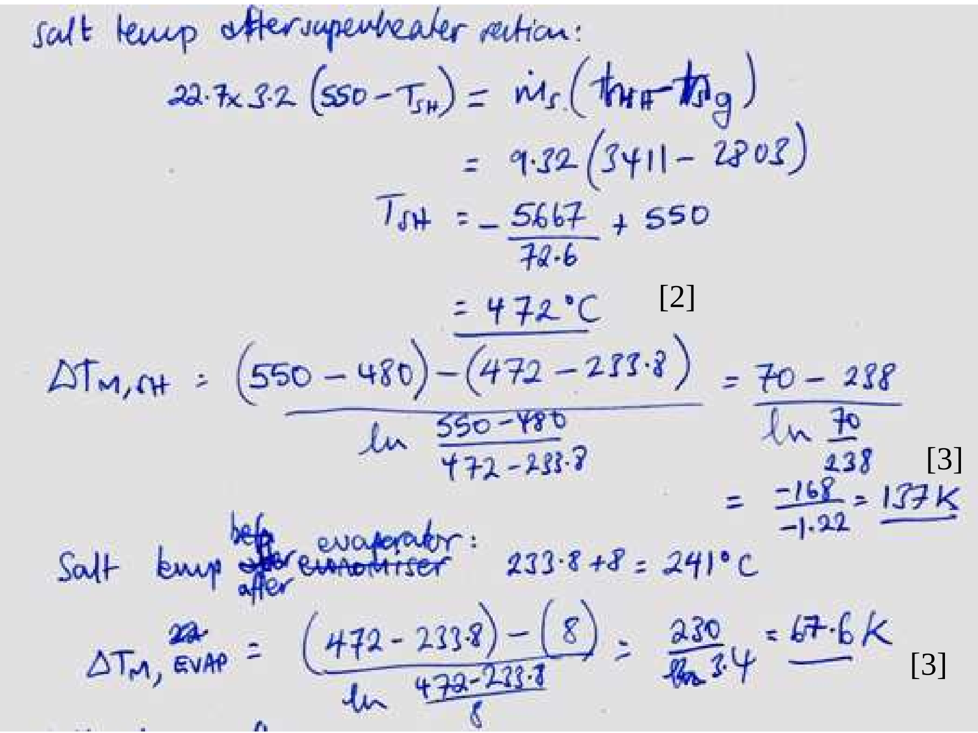
$\frac{480 - 450}{500 - 450} = \frac{h - 3343}{3456 - 3343}$

$\rightarrow h = \frac{30}{50} \times 113 + 3343$

$\eta_{TH} = W_{OUT}$ = 3411 − h

(b) Calculate the relative areas of the heat exchangers.

[17]



salt temp after superheater section:

$$22.7 \times 3.2\,(550 - T_{SH}) = \dot{m}_s\,(h_{SH} - h_g)$$

$$= 9.32\,(3411 - 2803)$$

$$T_{SH} = -\frac{5667}{72.6} + 550$$

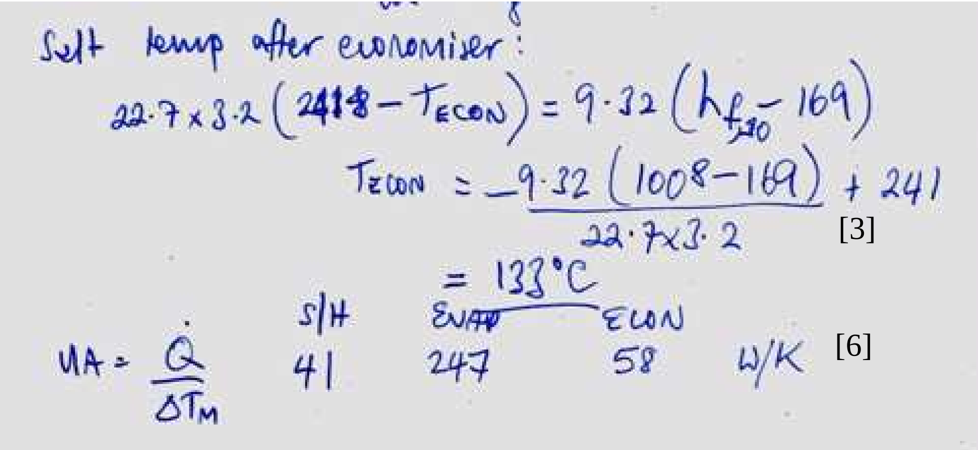
$$= \underline{472^\circ C}$$ [2]

$$\Delta T_{M,SH} = \frac{(550 - 480) - (472 - 233.8)}{\ln \frac{550-480}{472-233.8}} = \frac{70 - 238}{\ln \frac{70}{238}}$$ [3]

$$= \frac{-168}{-1.22} = \underline{137\,K}$$

Salt temp before ~~after~~ after ~~economiser~~ evaporator: 233.8 + 8 = 241°C

$$\Delta T_{M,EVAP} = \frac{(472 - 233.8) - (8)}{\ln \frac{472-233.8}{8}} = \frac{230}{\ln 3.4} = \underline{67.6\,K}$$ [3]



Salt temp after economiser:

$$22.7 \times 3.2\,(241 - T_{ECON}) = 9.32\,(h_{f,240} - 169)$$

$$T_{ECON} = -\frac{9.32\,(1008 - 169)}{22.7 \times 3.2} + 241$$ [3]

$$= 133^\circ C$$

$UA = \frac{\dot{Q}}{\Delta T_M}$

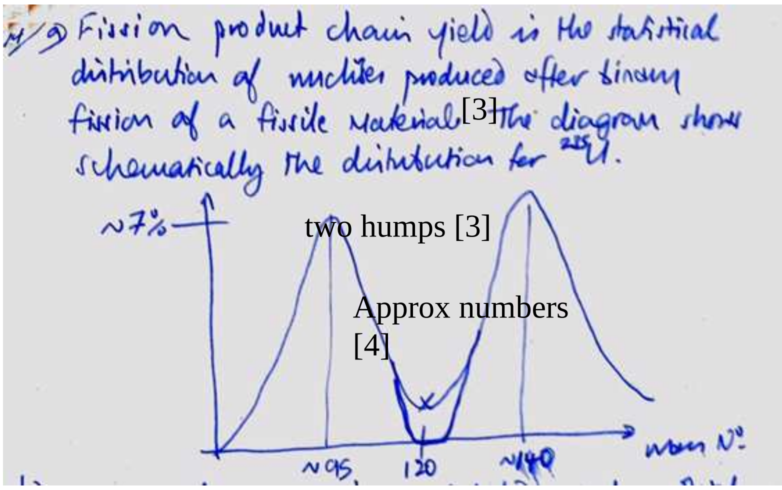
S/H	EVAP	ECON	
41	247	58	W/K

[6]

Steam chart accuracy is sufficient.

14. (a) Explain with the aid of a diagram the meaning of fission product chain yield for binary nuclear fission.

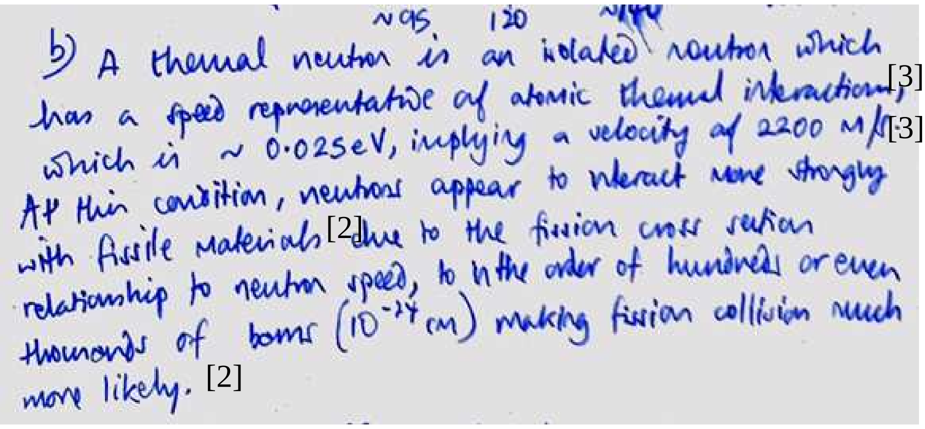
[10]



14 a) Fission product chain yield is the statistical distribution of nuclides produced after binary fission of a fissile material [3] The diagram shows schematically the distribution for ^{235}U.

(b) Explain the meaning of a thermal neutron and comment on the interaction behaviour with atomic nuclei.

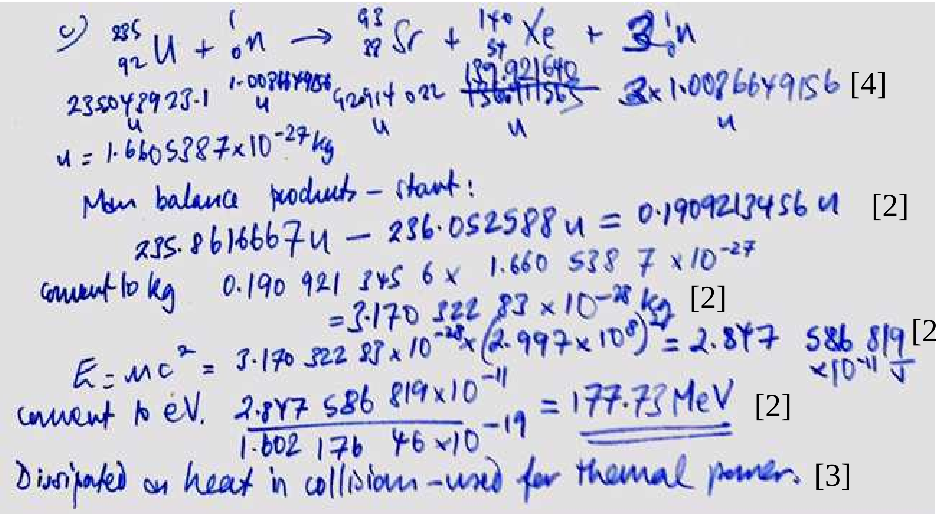
[10]



b) A thermal neutron is an isolated neutron which has a speed representative of atomic thermal interactions, [3] which is ~ 0.025eV, implying a velocity of 2200 m/s [3] At this condition, neutrons appear to interact more strongly with fissile materials [2] due to the fission cross section relationship to neutron speed, to in the order of hundreds or even thousands of barns (10^{-24} cm) making fission collision much more likely. [2]

(c) A ^{235}U (atomic mass 235.043 923 1u) nucleus undergoes interaction with a thermal neutron to produce $^{140}{}_{54}Xe$ (atomic mass 136.911 563u) and $^{93}{}_{38}Sr$ (atomic mass 92.914 022) with the associated release of three neutrons. Calculate the energy release and explain how this is dissipated.

[15]



c) $^{235}_{92}U + ^{1}_{0}n \rightarrow ^{93}_{38}Sr + ^{140}_{54}Xe + 3\,^{1}_{0}n$

235043923.1 u 1.00866491560 u 92914 022 u ~~136.911565~~ 139.921640 u 3 × 1.0086649156 u [4]

u = $1.6605387 \times 10^{-27}$ kg

Mass balance products − start:

235.8616667 u − 236.052588 u = 0.1909213456 u [2]

convert to kg 0.190 921 345 6 × 1.660 538 7 × 10^{-27}

= 3.170 322 83 × 10^{-28} kg [2]

$E = mc^2$ = 3.170 322 83 × 10^{-28} × $(2.997 \times 10^8)^2$ = 2.847 586 819 × 10^{-11} J [2]

convert to eV. $\frac{2.847\ 586\ 819 \times 10^{-11}}{1.602\ 176\ 46 \times 10^{-19}}$ = $\underline{\underline{177.73 \text{ MeV}}}$ [2]

Dissipated as heat in collisions – used for thermal power. [3]

END