

The University of Nottingham

DEPARTMENT OF MECHANICAL, MATERIALS AND MANUFACTURING ENGINEERING

A LEVEL 4 MODULE, SPRING SEMESTER 2015-2016

ADVANCED THERMAL POWER SYSTEMS

Time allowed ONE Hour and THIRTY Minutes

Candidates may complete the front cover of their answer book and sign their desk card but must NOT write anything else until the start of the examination period is announced

Answer ALL parts of QUESTION ONE and TWO other questions

Only silent, self contained calculators with a Single-Line Display or Dual-Line Display are permitted in this examination.

Dictionaries are not allowed with one exception. Those whose first language is not English may use a standard translation dictionary to translate between that language and English provided that neither language is the subject of this examination. Subject specific translation dictionaries are not permitted.

No electronic devices capable of storing and retrieving text, including electronic dictionaries, may be used.

DO NOT turn the examination paper over until instructed to do so

ADDITIONAL MATERIAL: Formula sheet
 Tables of Thermodynamic Properties of Fluids
 Enthalpy-entropy chart for Steam

INFORMATION FOR INVIGILATORS:

In case of any query with the exam paper during the examination, please contact the Module Convenor immediately on 07762328624.

Turn Over

1. Answer each part of this question

It should not be necessary to write more than about two or three sentences in answer to any part of this question.

All parts carry equal marks.

- (a) Evaluate the molar Gibbs Function of nitrogen gas at a temperature of 800K and a pressure of 30 bar (absolute).
- (b) Write the equation for the equilibrium constant for the following reaction in terms of partial pressures:
$$\text{H}_2\text{O} \Leftrightarrow \frac{1}{2} \text{H}_2 + \text{OH}$$
- (c) State the meaning of pinch temperature for a heat recovery steam generator and state why small pinch can be achieved with solar thermal using molten salt.
- (d) Use the non-steady flow energy equation to derive an expression for the flow of superheated steam into an initially evacuated closed vessel.
- (e) Briefly describe the operation of combustion carbon capture by amine absorption.
- (f) What is the rate of specific irreversibility in a steam turbine with steam entering at 160 bar and 500°C and exhausting adiabatically at 40 bar with enthalpy of 3050 kJ/kg and entropy 6.52 kJ/kgK? Take the ambient condition as water at 15°C.
- (g) State two advantages of an Integrated Coal Gasification Combined Cycle Power Plant over a conventional coal-fired power plant.
- (h) ^{135}Xe has a half-life of 9.2 hours. 'Decay' is by neutron absorption to the stable ^{136}Xe . What is the decay constant?
- (i) Describe the water-steam cycles of BWR and PWR nuclear reactors.
- (j) Calculate the speed of a neutron with a kinetic energy of 0.8 MeV.

2. A steady flow of pure carbon dioxide gas at a constant pressure of 8 bar (absolute) is heated from 25°C to a certain temperature. At this temperature the gas has dissociated and has the following composition by volume:

39.43% CO₂
40.38% CO
20.19% O₂

a) Calculate the final temperature of the gas. [15]

b) If the mass flow rate of the carbon dioxide is 0.03 kg/s, calculate the heat input required to raise the gas (at 8 bar) to the final temperature calculated above. Given that the enthalpy of each gas is:

$$\tilde{h}_i = \tilde{h}_{fi} + \Delta\tilde{h}_i$$

where the terms are in order: absolute enthalpy at temperature T, formation enthalpy at 25°C and enthalpy above the reference temperature 25°C.

[18]

3. An open cycle gas turbine has an air inlet temperature of 15°C, a pressure ratio of 8 across the compressor and a turbine entry temperature of 1127 °C. If the compressor and turbine both have a polytropic efficiency of 92%:

a) calculate the specific work output and thermal efficiency of the gas turbine. [13]

b) if a recuperator with an effectiveness of 75% is added to the gas turbine, calculate the improved thermal efficiency. [10]

c) explain why recuperative gas turbines are rarely used in practice. [10]

Assume that the working fluid is air throughout the gas turbine with a specific heat capacity of 1.005 kJ/kgK. Ignore pressure losses in the gas turbine combustion chamber and inlet and outlet ducts.

4. Exhaust gases from a gas turbine set are used to power a heat recovery steam generator. The hot gases enter at 713K and at a mass flow rate of 30 kg/s. The steam pressure in the HRSG is 85 bar and the final steam temperature at the outlet from the superheater is 380°C. Feedwater is supplied to the economiser at 30°C. The pinch temperature difference is 30K.
- a) Calculate the mass flow rate of steam and the temperature at which the gases leave the heat exchanger. [15]
- b) Calculate the total rate of irreversibility in the heat recovery boiler. [18]

Assume a specific heat capacity c_p of the exhaust gases of 1.13 kJ/kgK.
Assume an environmental temperature of 15°C.

5. a) Describe the terms in the four factor formula and what the formula is used for. [10 marks]
- b) What is the effective multiplication factor for a neutron lifecycle if the four factor formula is sufficient since the reactor is large? Given that fast fission factor, 1.06, resonance escape probability, 0.5, thermal utilisation factor, 0.95, and thermal fission factor, 1.95. What is the likely state of this reactor? (5 marks)
- c) What is the meaning of binding energy of a nucleus with regard to energy release by nuclear reactions? [5 marks]
- d) Describe with the aid of a schematic diagram why it is that fusion produces significantly more energy than fission. [8 marks]
- e) For a fission of $^{235}_{92}\text{U}$ (235.043 923 1 amu) into $^{132}_{53}\text{I}$ (131.907 995 amu) and $^{101}_{39}\text{Y}$ (101.930 310 amu) with the release of 1 neutron, calculate the energy released from the reaction. [5 marks]

END

ANSWERS:

1.

1 a) From tables, Gibbs function for nitrogen at 800K and 1 bar is: -161680 kJ/kmol .

$$\tilde{g} = h - T_s$$

\therefore from 1 bar to 30 bar, h is unaffected, but entropy is by entropy formula

$$\Delta \tilde{s} = -R \ln \frac{p_2}{p_1}$$

$$\therefore \Delta \tilde{g} = +\tilde{R}T \ln \frac{p_2}{p_1} = +8.314 \times 800 \times \ln 30 = +22,622 \text{ kJ/kmol}$$

$$\therefore \tilde{g}_{800K, 30 \text{ bar}} = -161680 + 22.622 = -139058 \text{ kJ/kmol}$$

$$b) K^\ominus = \frac{(p_{\text{H}_2\text{O}})}{(p_{\text{H}_2})^{1/2} (p_{\text{OH}})}$$

Inverse acceptable

c) The pinch temperature in heat recovery steam generator is the point in the heat exchanger where the gas enters the saturated liquid at the pressure of the system. In molten salt, heat exchange is very efficient due to high heat transfer coefficient, therefore smaller ΔT_{pinch} .

d) NSFEF:

$$\cancel{\frac{d}{dt} \sum m_i h_i} + \cancel{p \frac{dV}{dt}} = \sum m_i \left(h_i + \frac{C_p^2}{2} + g z_i \right) + \frac{d}{dt} m_{cv} \left(u_{cv} + \frac{C_{cv}^2}{2} + g z_{cv} \right) = \sum m_i \left(h_i + \frac{C_p^2}{2} + g z_i \right)$$

assume negligible k_p & p_e

$$\therefore \sum m_i h_i = \frac{d}{dt} m_{cv} u_{cv}$$

$$\int m_i h_i dt = \int u_{cv} dm_{cv} \Rightarrow h_i m_{cv} = m_{cv} u_{cv} \Rightarrow h_i = u_{cv}$$

e) Exhaust gas stream is passed through an amine mist in a venturi scrubber, absorbing the CO_2 . The amine with CO_2 is separated and the other gases are passed to exhaust whilst the amine is heated and the rebated CO_2 is captured.

f) $\dot{I} = \text{Exergy in} - \text{Exergy out}$.

$$\begin{aligned} \text{Exergy in} &= \dot{m} \left(h_1 - h_0 - T_0 (s_1 - s_0) \right) \text{ - formula sheet.} \\ &= \dot{m} \left(3300 - 62.9 - 288 (6.701 - 0.224) \right) \\ &= \dot{m} \times 1487 \text{ kW.} \end{aligned}$$

$$\begin{aligned} \text{Exergy out} &= \dot{m} \left(3050 - 62.9 - 288 (6.52 - 0.224) \right) \\ &= 1174 \dot{m} \text{ kW} \end{aligned}$$

$$\therefore \dot{I} = 313 \dot{m} \text{ kW}$$

g) With IGCC, CO_2 can be captured now easily, and the syngas can be used for CCGT.

h) half life of 9.2 hours.

$$T_{1/2} = \frac{0.693}{\lambda} \text{ - formula sheet; } 9.2 \text{ h is } 33,120 \text{ s.}$$

$$\therefore \lambda = \frac{0.693}{33120} = 2.09 \times 10^{-5} \text{ s}^{-1}$$

i) BWR has a single water-steam cycle which contacts the reactor core;

PWR has a high pressure - core contacting water heat transfer fluid with a heat exchanger to the steam raising cycle

$$k) 0.8 \text{ MeV} = 0.8 \times 10^6 \text{ eV} = 1.2817412 \times 10^{-13} \text{ J. (from formula)}$$

$$\begin{aligned} \therefore \frac{1}{2} m v^2 &= \frac{1}{2} \times 1.674927 \times 10^{-27} \times v^2 = 1.2817412 \times 10^{-13} \text{ J. (conversion)} \\ \therefore v &= 12.371 \times 10^6 \text{ m/s.} \end{aligned}$$



$$K^\theta = \frac{(p_{\text{CO}}) (p_{\text{O}_2})^{1/2}}{(p_{\text{CO}_2})} \cdot (p^\theta)^{1/2}$$

$$\text{or } K^\theta = \frac{(p_{\text{CO}_2})}{(x_{\text{CO}})(x_{\text{O}_2})^{1/2}} \left(\frac{p_{\text{TOT}}}{p^\theta} \right)^{1/2}$$

$$= \frac{0.4038}{0.3943} \cdot (0.2019)^{1/2} \cdot \left(\frac{8}{1} \right)^{1/2}$$

$$\therefore K^\theta = 1.302 \quad \text{ie } \ln K^\theta = 0.264$$

This is inverse of table's K^θ because the equation is other way round, for $\text{CO} + \frac{1}{2} \text{O}_2 \rightleftharpoons \text{CO}_2$ it is

-0.264

The temperature is therefore

3400-3600K, interpolation gives:

$$(T-3400)/(3600-3400) = (-0.264 - (-0.170)) / (-0.702 - (-0.170))$$

$$T = 3435 \text{ K}$$

2b) SFEE

$$Q = H_2 - H_1 \quad H = n h$$

$$H_1 = \sum n_i h_i \text{ reactants } 25^\circ\text{C (independent of } p)$$

$$H_2 = \sum n_i h_i \text{ products}$$

3400 K

8 bar.

Close enough to 3435 K for this case

$$h_i = \tilde{h}_f + \Delta \tilde{h}$$

$$H_2 = 0.3943 \tilde{h}_{\text{CO}_2} + 0.4038 \tilde{h}_{\text{CO}} + 0.2019 \tilde{h}_{\text{O}_2}$$

$$= 0.3943 (-893520 + 177850) + 0.4038 (-110520 + 108480)$$

$$+ 0.2019 (0 + 114230)$$

$$= -85038 + -828 + 23063 = -62803$$

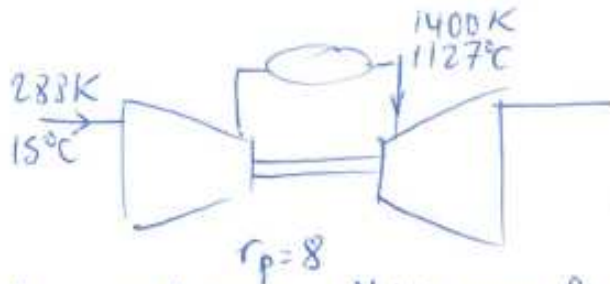
$$Q = H_2 - H_1 = -62803 - -892520$$

$$= 330717 \text{ kJ/kmol CO}_2$$

$$n_{\text{CO}_2} = \frac{0.03}{24} = 6.82 \times 10^{-4}$$

$$6.82 \times 10^{-4} \times 330717 \times 8 = \underline{\underline{225.5 \text{ kW}}}$$

3.



Using polytropic efficiency formula:

$$\text{Compressor } T_2 = T_1 \left(\frac{p_2}{p_1} \right)^{\frac{\gamma-1}{\gamma} \frac{1}{\eta_{\text{pol}}}} = 288 \times (8)^{\frac{0.4}{1.4} \times 1.12} = 549 \text{ K} = 276^\circ \text{C}$$

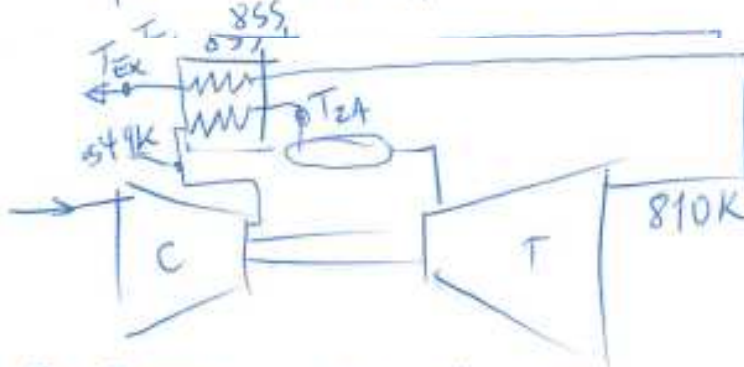
$$\text{turbine } T_4 = T_3 \left(\frac{p_4}{p_3} \right)^{\frac{\gamma-1}{\gamma} \eta_{\text{pol}} T} = 1400 \left(\frac{1}{8} \right)^{\frac{0.4}{1.4} \times 0.92} = 810 \text{ K} = 537^\circ \text{C}$$

$$\begin{aligned} W_{\text{specific}} &= c_p (T_3 - T_4) - c_p (T_2 - T_1) \\ &= 1.005 (1400 - 810) - 1.005 (549 - 288) \\ &= 593 - 262 = 331 \text{ kJ/kg} \end{aligned}$$

$$Q = c_p (T_3 - T_2) = 1.005 \times (1400 - 549) = 855 \text{ kJ/kg}$$

$$\therefore \eta_{\text{TH}} = \frac{331}{855} = 0.39$$

b)



$$E = \frac{q_{\text{ACTUAL}}}{q_{\text{MAX}}}$$

$$q_{\text{MAX}} = C_{\text{min}} \Delta T_{\text{MAX}}$$

$$C_{\text{min}} = C_{\text{MAX}} = C_{\text{AIR}} = \dot{m}_{\text{AIR}} c_{p,\text{AIR}} = 1.005 \text{ kJ/kg K}$$

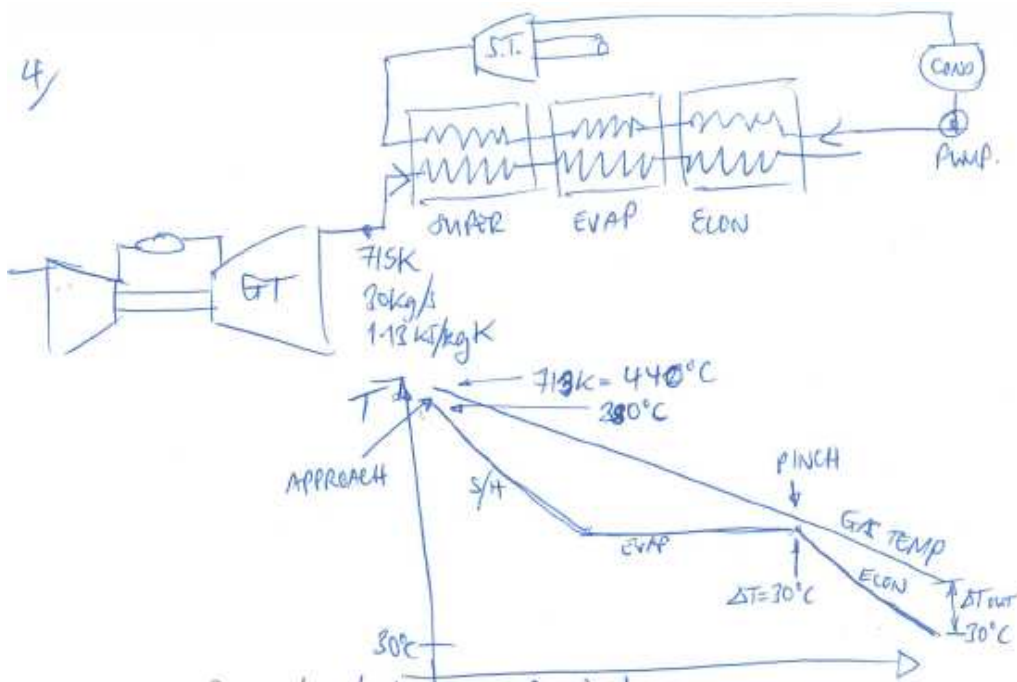
$$E = \frac{q_{\text{ACTUAL}}}{1.005 \times (810 - 549)} = 0.75 \rightarrow q_{\text{ACTUAL}} = 210 \text{ kW}$$

This q heats up the compressed gas at T_2 to T_{2a}

$$210 = 1.005 (T_{2a} - 537) \rightarrow T_{2a} = 745 \text{ K}$$

$$\therefore Q = c_p (T_3 - T_{2a}) = 1.005 (1400 - 745) = 658 \text{ kJ/kg} \quad \eta_{\text{TH}} = 0.51$$

c) size of heat exchanger 4, not really effective for high compression ratio Z ; only useful for land and water based power sets 2; cost of heat exchanger 2.



Mass flow rate of steam is found by:

$$(\dot{m} \Delta h)_{\text{gas}} = (\dot{m} \Delta h)_{\text{steam}} \text{ from pinch to approach}$$

$$\therefore 30 \times C_p \times (440 - T_{g, \text{pinch}}) = \dot{m}_s \cdot (h_{gH} - h_f)$$

$T_{g, \text{pinch}}$ is $T_{\text{sat}} + 30^\circ\text{C}$.

At 85 bar, T_{sat} is by interpolation on tables:

$$T_{\text{sat}, 85 \text{ bar}} = 295^\circ\text{C} \rightarrow 299.2^\circ\text{C} \text{ (p.5)}$$

$$T_{\text{sat}} + 30 = 329.2^\circ\text{C} = T_{g, \text{pinch}}$$

h_f is saturation enthalpy at 85 bar, p.5 tables

$$h_f = 1341 \text{ kJ/kg}$$

3

h_{gH} is by interpolation:

85 bar is mid-way between 80 & 90 bar \therefore average h

$$h_{375^\circ\text{C}, 85 \text{ bar}} = \frac{3067 + 3042}{2} = 3055 \text{ kJ/kg}$$

$$h_{400^\circ\text{C}, 85 \text{ bar}} = \frac{3139 + 3118}{2} = 3129 \text{ kJ/kg}$$

\therefore Interpolate for 440°C :

$$\frac{380 - 375}{400 - 375} = \frac{h_{380} - 3055}{3129 - 3055} \rightarrow h_{380} = 3070 \text{ kJ/kg}$$

5

$$\therefore 30 \times 1.13 \times (440 - 329.2) = \dot{m}_s (3070 - 1341)$$

$$\dot{m}_s = 2.17 \text{ kg/s.} \quad \boxed{2}$$

Temperature of gas leaving is by enthalpy across economiser:

$$\dot{m}_g \Delta T_{g,econ} = \dot{m}_s \Delta h_{steam,econ}$$

$$30 \times 1.13 \times (329.2 - T_{g,out}) = 2.17 \times (1341 - h_{f,30^\circ\text{C}})$$

$$h_{f,30^\circ\text{C}} = 125.7 \text{ kJ/kg}$$

$$\therefore 33.9 (329.2 - T_{g,out}) = 2637$$

$$\therefore T_{g,out} = 251.4^\circ\text{C} \quad \boxed{5}$$

b/ Irreversibility is $\dot{I} = \text{Exergy in} - \text{Exergy out}$.

Exergy in is by gas change & Exergy out is by steam change.

$$E_{g,in} = c_p (T_1 - T_0) - T_0 c_p \ln \frac{T_1}{T_0} \quad (\text{no } \Delta p)$$

$$E_{g,in} = 1.13 \left(\boxed{480} - 15 \right) - 288 \times 1.13 \times \ln \frac{\boxed{753}}{288} = \boxed{213} \text{ kJ/kg}$$

$$E_{g,out} = 1.13 \left(\boxed{267} - 15 \right) - 288 \times 1.13 \times \ln \frac{524}{288} = \boxed{72} \text{ kJ/kg}$$

$$\therefore \dot{E}_i = \dot{m}_g (E_{g,in} - E_{g,out}) = 30 \times (213 - 72) = \underline{3399} \text{ kW.} \quad \boxed{7}$$

$$E_{steam,in} = (h_1 - h_0) - T_0 (s_1 - s_0)$$

$$E_{steam,in} = (h_{f,30^\circ\text{C}} - h_{f,15^\circ\text{C}}) - 288 (s_{f,30^\circ\text{C}} - s_{f,15^\circ\text{C}})$$

$$= (125.7 - 62.9) - 288 (0.436 - 0.224) = 1.744 \text{ kJ/kg}$$

$$E_{steam,out} = (h_{gH,380^\circ\text{C}} - h_{f,15^\circ\text{C}}) - 288 (s_{gH,380^\circ\text{C}} - s_{f,15^\circ\text{C}})$$

$$= (3070 - 62.9) - 288 (s_{gH,380^\circ\text{C}} - 0.224) =$$

Need $s_{gH,380^\circ\text{C}}$, from tables given between 80 & 90 bar:

$$s_{85 \text{ bar}, 375^\circ\text{C}} = \frac{6.255 + 6.171}{2} = 6.213 \text{ kJ/kgK}$$

$$s_{85 \text{ bar}, 400^\circ\text{C}} = \frac{6.364 + 6.286}{2} = 6.325 \text{ kJ/kgK}$$

$$\text{Interpolate: } \frac{380 - 375}{400 - 375} = \frac{s - 6.213}{6.325 - 6.213} \rightarrow s = 6.235 \text{ kJ/kgK}$$

$$\therefore E_{\text{STEAM OUT}} = 1276 \text{ kJ/kg}$$

$$\begin{aligned} \therefore \dot{E}_{\text{OUT}} &= \dot{m}_s (E_{\text{STEAM OUT}} - E_{\text{STEAM IN}}) \\ &= 2.17 (1276 - 1.74) \\ &= 2765 \text{ kW.} \end{aligned}$$

$$\therefore \dot{I} = 3399 - 2765 = 634 \text{ kW.}$$

5.

By the four factor formula calculates the effective multiplication factor, k_{eff} , which is the rate of

① - increase of neutron population in the reactor. It depends on:

i) fast fission factor, $\epsilon = \frac{\text{total fissions}}{\text{thermal only fissions}}$ and allows

② - for the less likely fissions caused by fast neutrons

ii) resonance escape probability, $p = \frac{\text{neutrons reaching thermal}}{\text{neutrons absorbed before thermal}}$

③ - and allow for absorption of neutrons before they have slowed sufficiently to ^{cause} fission

iii) thermal utilization factor, $f = \frac{\text{neutron absorption in fuel}}{\text{neutron absorption in moderator}}$

④ - and allow for neutrons lost to the population by absorption in moderator.

⑤ - iv) thermal fission factor, $\eta = N'_{\text{thermal}} \times \text{probability of thermal fission}$

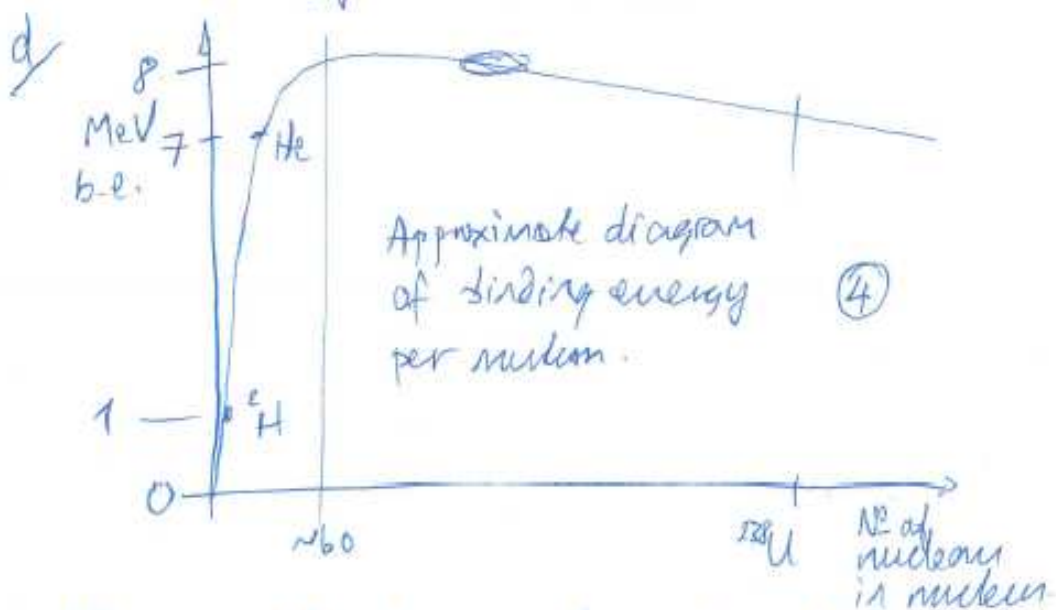
⑥ - $k_{\text{eff}} = \frac{n'}{n}$, where n is the starting neutron ^{cloud} number and n' is the next generation number.

$$\therefore k_{\text{eff}} = \epsilon p f \eta = 1.06 \times 0.5 \times 0.95 \times 1.95 = 0.98.$$

This is a subcritical reactor.

c/ Binding energy is the energy required to bind a nucleus together⁽²⁾ due to the Einstein mass change required to overcome nuclear forces. It is an energy release to bind⁽¹⁾

Therefore by going from a nucleus with a low binding energy to a higher binding energy, more energy will be released.



^{238}U generally fissions to two parts in the order of half the original nuclear number and a change of about 1 MeV per nucleon results⁽²⁾

^2H fuses to make ^4He with a change of 1 to 7 MeV.⁽²⁾

e/ Energy released is difference in mass converted by Einstein equation to energy:

$$235.0439221 - 131.907995 - 101.970310 - 1.008664915$$

$$= 0.176953 \text{ amu} \rightarrow \times 1.6605387 \times 10^{-27} = 2.93936428 \times 10^{-28}$$

$$\text{convert to energy } E = 2.93936428 \times 10^{-28} \times (2.99792458 \times 10^8)^2$$

$$= 2.93936428 \times 10^{-11} \text{ J or } \underline{183 \text{ MeV.}}$$