NTNU – Trondheim
Norwegian University of
Science and Technology

Department of Physics

Examination paper for TFY4300: Energy and Environmental Physics

Academic contact during examination: Rob Hibbins
Phone: 94820834

Examination date: 08-12-2014
Examination time: 09:00 – 13:00
Permitted examination support material:

- Calculator (any, code A)
- Dictionary (ordinary or bi-lingual)
- Printed or hand-written notes covering a maximum of one side of A5 paper.

Other information: The exam is in two parts. Part 1 is multiple choice, part 2 is written answers. Answer all questions in both parts. The percentage of marks awarded for each question is shown. An Appendix of useful information is provided at the end of the question sheet.

Language: English
Number of pages: 7 (including cover)
Number of pages enclosed: 0

Checked by:

Date Signature

Part 1. Multiple Choice Questions (60%).

Answer all questions. There is only **one** correct answer so you must **choose the best answer**. Answer A, B, C… (Capital letters). A correct answer gives 3 percentage points towards the final score. Incorrect answers, blank (unanswered) questions, or multiple answers to the same question will be awarded 0 points.

Only the answer will be marked.

Write the answers for the multiple choice questions **on the answer sheet you turn in** using a table similar to the following:

Question	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Answer	**D**	**C**	**A**	**C**	**B**	**E**	**A**	**C**	**A**	**E**	**D**	**B**	**A**	**A**	**A**	**C**	**C**	**D**	**A** **D**	**A**

1. Calculate the wavelength (λ_{max}) for the maximum intensity of the black body radiation from a human being, assuming a surface temperature of 32°C.
   A. 15 microns
   B. 0.2 microns
   C. 500 nm
   D. 9.5 microns
   E. 794 nm

λ_{max} = 2898/(32+273) = 9.5 microns

2. Assume that the surface area of a human being is 2m^2 and that they radiate energy at a rate 97% that of a blackbody (the emissivity, ε=0.97). Calculate the total emitted power of the person with a surface temperature of 32°C.
   A. 200 W
   B. 5 kW
   C. 950 W
   D. 2 W
   E. 5 W

$P_{emit} = \varepsilon\sigma_B T^4 A = 0.97 \times 5.67 \times 10^{-8} \times (32+273)^4 \times 2 = 950\text{W}$

3. If the person discussed in question 2 is standing in a room at 15°C, estimate the net power emitted by the person into the room.

   A. 200 W
   B. 5 kW
   C. 950 W

D. 2 W
E. 5 W

$P_{net} = P_{emit} - P_{abs}$ = 950W – (0.97 x 5.67 x 10^{-8} x $(15+273)^4$ x 2) = 200W

4. One of the many fission reactions that takes place when a slow neutron strikes a ^{235}U nucleus in a nuclear reactor results in the formation of Ba and Kr in the following reaction:

$$^{235}_{92}\mathbf{U}_{143} + {}^{1}_{0}\mathbf{n}_{1} = {}^{236}_{92}\mathbf{U}_{144} = {}^{90}_{36}\mathbf{Kr}_{54} + {}^{144}_{56}\mathbf{Ba}_{88} + \nu \cdot {}^{1}_{0}\mathbf{n}_{1} + Energy$$

How many neutrons, ν, will be emitted in this process?

A. 0, only gamma rays will be given off
B. 1
C. 2
D. 2.43 on average
E. 4

236 = 90 + 144 +2

5. The current abundance of the two most common isotopes of naturally occurring Uranium found on Earth is 0.7% ^{235}U and 99.3% ^{238}U. If the half-life for spontaneous decay of ^{238}U is 4.5 x 10^9 years and the half-life for spontaneous decay of ^{235}U is 7.0 x 10^8 years, calculate what the Uranium isotope ratio on Earth was 2x10^9 years ago.

A. 0.7% ^{235}U and 99.3% ^{238}U
B. 3.7% ^{235}U and 96.3% ^{238}U
C. 7.3% ^{235}U and 92.7% ^{238}U
D. 0.1% ^{235}U and 99.9% ^{238}U
E. 50% ^{235}U and 50% ^{238}U

$N(t) = N_0 \exp(-t/\tau)$ and $\tau = t_{1/2}/\ln(2)$

^{235}U was 7.39 times more abundant than now, ^{238}U was 1.36 times more abundant than now.

ratio = 142*1.36/7.39 = 26.13 ^{238}U for each ^{235}U = 96.3% ^{238}U and 3.7% ^{235}U

6. A pressurized water reactor undergoes approximately 7.8x10^{19} fissions of ^{235}U per second. What is the mass of ^{235}U that undergoes fission in a 4-year fuel cycle? Take the atomic mass of ^{235}U to be 235.04394 atomic mass units.

A. 2880 kg
B. 391287 kg
C. 900 kg
D. 16200 kg
E. 3800 kg

7.8 x 10^{19} x 86400 x 365 x 4 fissions = 9.84 x 10^{27} fissions
each atom weighs 235/6.02 x 10^{23} g = 3.9 x 10^{-22} g
multiply them together = 3838 kg

7. In an un-illuminated (i.e. dark) silicon based solar cell, in which direction does the "built in" electric field point?
    A. Points from + in n-type material to - in p-type
    B. Points from + in p-type material to - in n-type material
    C. Without illumination there is no E field in the device
    D. Points from + in valence band to - in the conduction band
    E. Points from the + hole carriers in the valence band to the - electron carriers in the conduction band

N to P as the negatively charged free carriers migrate from the N side leaving a net +ve charge (and vice versa)

8. What is the temperature of an isothermal atmosphere in which the pressure is 1025 hPa at the surface and 525 hPa at a height of 5 km? (NB: 1hPa = 100 Pa)
    A. 273K
    B. 246K
    C. 255K
    D. +16°C
    E. +26°C

$dp/dz = -g\rho(z)$ and $p(z) = RT(z)\rho(z)$, so $\ln(P_2/P_1) = -g(z_2-z_1)/RT$ (isothermally)

T = 255K

9. If the surface pressure at the North Pole is 950 hPa, calculate the altitude where the atmospheric pressure is 200 hPa assuming an isothermal atmosphere at a temperature of -30°C
    A. 11 km
    B. 19 km
    C. 19 m
    D. 4 km
    E. 120 km

as above, z_2 = 11km

10. With an albedo of 0.3 and an atmosphere with a long-wavelength transmission of 0.15 and a short wavelength transmission of 0.85 we have seen that the equilibrium temperature of the Earth is around 287 K. A gas is introduced into the atmosphere that decreases the mean long wavelength transmission of the atmosphere from 0.15 to 0.12. If the mean short wavelength transmission of the atmosphere remains unchanged at 0.85 and the albedo remains at 30%, what is the resulting temperature of the Earth?

    A. 287 K
    B. 285 K
    C. 293 K
    D. 300 K
    E. 289 K

$\varepsilon\sigma_B T_e^4 = (S(1-a)/4).((1+\tau_s)/(1+\tau_L))$, solve for ε/S:

$\varepsilon/S = (0.7/(4\text{x}5.7\text{x}10^{-8}\text{x}287^4))(1.85/1.15) = 7.28\text{x}10^{-4} m^2/W$ substitute at a new τ_L

$T_{new} = 289K$

11. The Bay of Fundy is 260 km long and about 50 m average depth. Calculate the fundamental resonant period of this bay.

    A. 12.5 hours
    B. 47 s
    C. 6.5 hours
    D. 13 hours
    E. 22.1 hours

$T_r = 4L/j(gh)^{1/2} = 4\text{x}260000/\text{sqrt}(9.8\text{x}50) = 13$ hours

12. The Bay of Fundy has a surface area of 16,000 km^2, and the semi-diurnal (12.5 hour) tidal range varies between 6 and 16 meters. What average power could be obtained if one built a barrage dam across the whole bay? Take the density of seawater to be 1035 $kg{\cdot}m^{-3}$.

    A. 300 GW
    B. 263 GW
    C. 948 MW
    D. 263 MW
    E. 180 GW

$P = (\rho Ag/2\tau).(R_{max}^2 + R_{min}^2)/2 = 2.63 \text{ x } 10^{11}$ W

13. Calculate the mean power produced by a tidal stream turbine in a semi-diurnal (12.5 hour) tidal stream of maximum amplitude (u_0) 4m/s. Assume the turbine has a diameter of 5m, and runs at an efficiency of 75% of the Betz limit and the density of sea water is 1035 kg/m^3.

    A. 121 kW
    B. 6.2 kW
    C. 205 kW
    D. 10.5 kW
    E. 6624 W

$q = \eta(\rho/2)u_0^3(4/3\pi) = 0.75 \text{ x } 0.59 \text{ x } (1035 / 2) \text{ x } 4^3 \text{ x } 4 / (3\pi) = 6.2 \text{ kW/m}^2 \text{ x } \pi \text{ x } 2.5^2 = 121$ kW

14. How does the energy transport for a sinusoidal wave propagating in deep water change as one goes deeper in the water?

    A. The energy flow density decreases.
    B. The energy flow density remains the same
    C. The energy flow density increases
    D. There is not any energy flow density under the surface.

15. The volume of seawater (molar mass 18g/mol, density 1030 kg/m^3) on the Earth is $1.37\text{x}10^9$ km^3. If 200 of every million hydrogen atoms in the water are in the form of

deuterium how much energy could one extract from the seawater using a deuterium/deuterium fusion reaction that produces 4 MeV of energy per fusion?

A. $6 x 10^{30}$ J
B. $1.2 x 10^{31}$ J
C. $3 x 10^{30}$ J
D. $6 x 10^{24}$ J
E. $3 x 10^{24}$ J

$1.37x10^9$ km^3 =$1.37x10^{18}$ m^3 = $1.41 x 10^{21}$ kg = $7.84 x 10^{22}$ mol = $4.72 x 10^{46}$ molecules = $9.44 x 10^{46}$ H atoms = $1.89 x 10^{43}$ D atoms = $9.44 x 10^{42}$ fusions = $3.78 x 10^{49}$ eV = $6.04 x 10^{30}$ J

16. The heat of combustion of an organic compound used as a bio fuel is approximately equal to 450kJ per mole of carbon per reduction level, use this to estimate the heat of combustion of ethanol (C_2H_5OH, molar mass of 46g/mol).

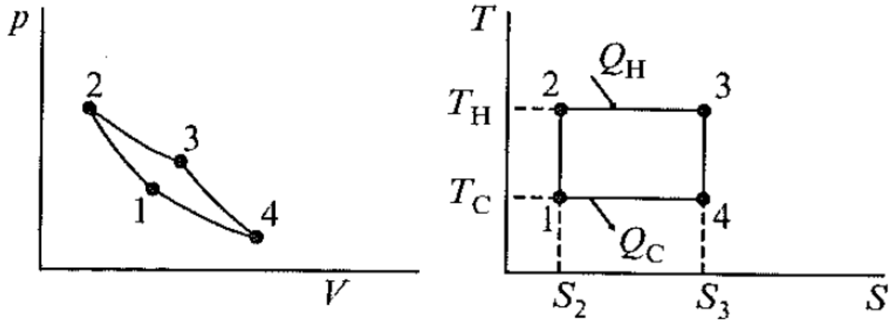
A. 450 kJ/mol
B. 900 kJ/mol
C. 29 MJ/kg
D. 15 kJ/g
E. 300 kJ/kg

R=(c+0.25h-0.5o)/c = (2+1.5-0.5)/2 = 1.5
1 mol ethanol = 2 mol carbon at R = 1.5 = 1350 kJ/46g = 29MJ/kg

17. The world consumption of primary energy in 2013 was 12730 MTOE. Assume that the wind blows at 13m/s for 1/3 of the time (and that there is no wind at other times), that the efficiency of a wind turbine is 70% of the maximum theoretical value and the density of air is 1.2 kg/m^3. How many wind turbines with a diameter of 60m would be needed to supply this total energy?

A. $1.1x10^4$ turbines
B. $5.6x10^7$ turbines
C. $3.3x10^7$ turbines
D. $1.1x10^7$ turbines
E. $1.3x10^8$ turbines

12730 MTOE = $5.3 x 10^{20}$ J, A = 2827 m^2
P_t = (0.5 x ρ x A x u_0^3 x 0.7 x 0.59)/3 = 513 kW per turbine = $1.62 x 10^{13}$ J/(turbine.year), so $3.28 x 10^7$ turbines are required.



The final three multiple choice questions (18-20) refer to the diagram above which represents the Carnot thermodynamic cycle on a pressure-volume grid (left) and a temperature-entropy grid (right)

18. Which process represents an adiabatic expansion of the working gas?

A. 1→2
B. 2→3
C. 1→4
D. 3→4
E. none of the above

19. The total work done by the gas on the surroundings during each cycle is given by:

A. The area under the curve 2→3→4 on the pV diagram
B. The area under the line 2→3 on the TS diagram
C. The average gradient of the curve 2→3→4 on the pV diagram
D. The area enclosed by the four curves on the pV diagram
E. $S_3 – S_2$

Both solutions (A or D) were marked correct as the wording of the question was deemed ambiguous.

20. The thermodynamic efficiency of this cycle is given by:

A. $1-(T_C/T_H)$
B. $1-(T_H/T_C)$
C. $(1-T_C)/T_H$
D. $(T_C-T_H)/T_H$
E. none of the above

Part 2. Calculations (40%)

Answer all questions. The number in brackets represents the contribution of each sub-question to the total score.

For derivations of the equations used in this question see Twiddel and Weir 475-478 (also worked through on the board and in notes from week07)

1. (a) In a normal geothermal region the temperature increases with depth at around 40°C/km. Calculate the useful heat content per square km of dry granite rock up to a depth of 7 km in this geothermal region. Assume the minimum useful temperature is 140°C above the ambient surface temperature. The density of granite is $2700 kg/m^3$ and the heat capacity of dry granite is 820 J/(kgK). (6%)

so, $z_1 = 3.5km$, $z_2 = 7km$ $T_1 = 140°C$, $T_2 = 280°C$, and $E_0/A = \rho C_r(\Delta z)(\Delta T)/2 = 5.4 \times 10^{11}\ J/m^2 = 5.4 \times 10^{17}\ J/km^2$

(b) This useful heat can be extracted by fracturing the hot granite and pumping water through the fractured rocks. What is the time constant for useful heat extraction using water at a flow rate of $1m^3/(s.km^2)$? You can assume the density of water is $1g/cm^3$ and the heat capacity of water is 4.2 kJ/(kgK). (6%)

$\tau = \rho_r A C_r(\Delta z)/\rho_w U C_w$ where A/U is $10^6\ m^2/(m^3/s)$, so $\tau = 58.5$ years

(c) Over time the source fades as the useful heat is extracted much quicker than it can be replenished by conduction from the surrounding rocks. What is the useful heat extraction rate after 20 years of extraction using water at a flow rate of $1m^3/(s.km^2)$? (8%)

$E(t)/A = E_0/A \exp(-t/\tau)$, it's an exponential decay, so at t=0 $d(E/A)/dt = E_0/A\tau = 5.42\times10^{11} J/m^2/58.5years = 294\ W/m^2$, and after 20 years $d(E/A)/dt = 294 \exp(-20/58.5) = 209\ W/m^2$

2. The Dinorwig pumped-storage facility is a hydroelectric power station in North Wales, UK. Water is pumped from a low altitude lake (called Llyn Peris) to a high altitude reservoir (called Marchlyn Mawr). From there, valves can be opened to drain the water from Marchlyn Mawr (at a flow rate of $390\ m^3/s$) through turbines to generate electricity when required. The total volume of water held in Marchlyn Mawr is $7.6\times10^6\ m^3$ at a mean height of 568m above the turbines. The density of fresh water is $1\ g/cm^3$.

(a) What is the total useful energy stored in Marchlyn Mawr when full? Express your answer in GWhr (gigawatt hours). (5%)

$mgh = 7.6\times10^6 \times 10^3 \times 9.8 \times 568 = 4.23 \times 10^{13}\ J = 11.8$ GWhr

(b) If the total losses in the system result in the electric power being generated at an efficiency of 75%, calculate the average electric power generated by the turbines when the valves are fully open. (4%)

e.g. in 1 sec 390×10^3 kg $\times 9.8 \times 568 \times 0.75 = 1.63 \times 10^9$ J/s

(c) What is the maximum amount of time this power can be produced before having to refill Marchlyn Mawr? (3%)

$7.6\times10^6/390 = 5.41$ hours

(d) If the water from Llyn Peris can be pumped back up to Marchlyn Mawr at 90% efficiency what is the net energy taken from the UK electricity grid by one complete fill-empty cycle of this facility? Express you answer in GWhr. (4%)

$E_{to\ grid} = 4.23 \times 10^{13}$ J x 0.75 = 3.17×10^{13} J

$E_{from\ grid} = (1/0.9) \times 4.23 \times 10^{13}$J = 4.70×10^{13}J

net = 1.53×10^{13} J = 4.25 GWhr from grid each cycle

(e) If it takes more energy from the grid than it delivers over one complete cycle, why has this facility been built? (4%)

A discussion on <u>high frequency</u> grid load variability (e.g. diurnal cycle and/or "TV-pickup") is required here. Water is pumped up during times of <u>low demand/high capacity</u> and released during times of <u>high demand/low capacity</u>. Could also mention that Dinorwig is designed to provide the initial power to restart the grid in the event of a total UK-wide grid shutdown.

APPENDIX

Physical constants and conversions

Planck's constant: $h = 6.626 \times 10^{-34}$ Js

The speed of light: $c = 2.998 \times 10^{8}$ m/s

Boltzmann's constant: $k = 1.38 \times 10^{-23}$ J/K

Stefan-Boltzmann's constant: $\sigma_B = 5.67 \times 10^{-8}$ W/(m^{2}K^4)

Avogadro's number: $N_A = 6.022 \times 10^{23}$ mol^{-1}

The electron charge: $e = 1.602 \times 10^{-19}$ C

The radius of the sun: $r_s = 6.96 \times 10^{8}$ m

The radius of the earth: $r_e = 6.4 \times 10^{6}$ m

The mean sun-earth distance: $\mathrm{d}_{se} = 1.49 \times 10^{11}$ m

Specific gas constant for dry air: $R_{air} = 287$ J·K^{-1}·kg^{-1}

1 ha = 10^4 m^2 1TW·h·yr^{-1} = 10^{12} W·h·yr^{-1} = 10^{12} W·h·yr^{-1}/(24 · 365h·yr^{-1}) = 1.14 x 10^8 W

1 eV = 1.602 x 10^{-19} J 1 amu = 1.66 x 10^{-27} kg 1 TOE = 42 x 10^9 J

0°C = 273.15K

List of equations

$pV = nRT$ $p = \rho R_{air} T$	$P_{ij} = \frac{\Delta T}{R_{ij}}$	
$\frac{\partial p}{\partial z} = -\frac{p}{H}$	$q = \frac{P}{A} = \frac{\Delta T}{r}$	
$\frac{\partial T}{\partial z} = -\frac{g}{c_p} = -\Gamma_d$	$r = \frac{1}{h} = RA$	
$H = \frac{R_{air} \cdot T}{g}$	$r_n = \frac{\Delta x}{k}$ $R_n = \frac{\Delta x}{kA}$	
$E = h\upsilon$	$\eta = \frac{W}{Q_H}$	
$I_E dE = \frac{2\pi\nu^3}{c^2}\frac{1}{e^{h\upsilon/kt} - 1} dE$	$\alpha_\lambda + \rho_\lambda + \tau_\lambda = 1$ $P_r = A\varepsilon\sigma T^4$	
$I_\lambda = \frac{2\pi hc^2}{\lambda^5}\frac{1}{e^{hc/\lambda kt} - 1}$		
$\lambda_{max} T = 2898[\mu m\ K]$		
$I(T) = \sigma T^4$		
$P_T = IV$		

$$^{235}\text{U}+\text{n}\rightarrow {}^{236}\text{U}\rightarrow X+Y+\upsilon\text{n}+\text{energy}$$

$$\eta=\nu\frac{N(235)\sigma_f(235)}{N(235)\left[\sigma_f(235)+\sigma_c(235)\right]+N(238)\sigma_c(238)}$$

$$\frac{dN}{dt}=\frac{\rho N}{l}$$

$$N(t)=N_0\exp(-t/\tau)$$

$$l^*=(1-\beta)l+\beta t_d$$

$$^{2}\text{D}+{}^{3}\text{T}\longrightarrow {}^{4}\text{He}+{}^{1}\text{n}+17.6\text{MeV}$$

$$T=T_0+Gz$$

$$\tau=\rho_r Ac_r(z_2-z_1)/\dot{V}\rho_w c_w$$

$$E(t)=E_0\exp(-t/\tau)$$

$$F_g=\frac{Gm_1m_2}{R_{12}^2}\qquad F_c=mR\omega^2$$

$$\frac{GMM'}{D^2}=ML\omega^2=M'L'\omega^2$$

$$\frac{\partial^2 z}{\partial t^2}=gh\frac{\partial^2 z}{\partial x^2}=c^2\frac{\partial^2 z}{\partial x^2};\qquad c=\sqrt{gh}$$

$$T_r=\frac{\lambda}{c}=\frac{4L}{jc}=\frac{4L}{j\sqrt{gh}}$$

$$\bar{\text{P}}=\frac{\rho AR^2}{2}g\cdot\frac{1}{\tau}=\frac{\rho Ag}{2\tau}R^2\qquad \bar{\text{P}}\approx\frac{\rho Ag}{2\tau}\left(\frac{R_{\max}{}^2+R_{\min}{}^2}{2}\right)$$

$$q=\frac{P}{A}=\frac{\rho u^3}{2}$$

$$\bar{q}=\eta\frac{\rho\overline{u^3}}{2}=\eta\frac{\rho}{2}\frac{u_0^3\int_{t=0}^{t=\tau/4}\sin^3(2\pi t/\tau)dt}{\int_{t=0}^{t=\tau/4}dt}=\frac{\eta\rho u_0^3}{2}\left(\frac{4}{3\pi}\right)$$

$$\frac{1}{(D\pm r)^2}=\frac{1}{D^2}\left(1\mp\frac{2r}{D}\right)$$

$$V_B=\frac{E_g}{e}-\left(\phi_n+\phi_p\right)$$

$$I(V)=I_L-I_D=I_L-I_0\left[\exp\left(\frac{eV}{AkT}\right)-1\right]$$

$$\Delta\mu=E_{Fn}-E_{Fp}=eV$$

$$\eta=\frac{I_{\text{m}}\cdot V_m}{P_{in}}=FF\cdot\frac{I_{sc}\cdot V_{oc}}{P_{in}}$$

$$FF=\frac{I_{\text{m}}\cdot V_m}{I_{sc}\cdot V_{oc}}$$

$$\rho=\frac{(n_0-n_1)^2}{(n_0+n_1)^2}$$

$$CO_2+H_2\dot{O}\xrightarrow{light}\dot{O}_2+\left[CH_2O\right]+H_2O$$

$$P_T=C_PA\frac{\rho u_0^3}{2}$$

$$P_o=A\frac{\rho u_0^3}{2}$$

$$F_A=\frac{\Delta\text{p}}{\Delta t}=\frac{m(u_0-u_2)}{\Delta t}=\rho A_1u_1(u_0-u_2)$$

$$F_A=A_1(p_{1u}-p_{1d})=A_1\rho(u_0{}^2-u_2{}^2)/2$$

$$P=u_1F_A$$

$$P_T=u_1F_A=u_1\frac{dm}{dt}(u_0-u_2)$$

$$P_T=\frac{1}{2}\frac{dm}{dt}(u_0{}^2-u_2{}^2)$$

$$a=\frac{u_0-u_1}{u_0}$$

$$P_T=\left[4a(1-a)^2\right]P_0$$

$$C_P\le\frac{16}{27}$$