TU/e Technische Universiteit Eindhoven University of Technology

Examination cover sheet

(to be completed by the examiner)

Course name: Physics of New Energy source Course code: 3DEX1

Date: 26/01/2016

Start time: 9:00 End time: 12:00

Number of pages: 7 (incl. this)

Number of questions: 4

Maximum number of points/distribution of points over questions: 100 (Q1: 15, Q2: 15, Q3: 35, Q4: 35)

Method of determining final grade: 1.0+0.09xnumber of points

Answering style: formulation, order, foundation of arguments, multiple choice: formulation

Exam inspection: 25 /02/2016: 12.45-13.30 Location Flux 0.01

Other remarks:

Instructions for students and invigilators

Permitted examination aids (to be supplied by students):

- □ Notebook
- x Calculator
- □ Graphic calculator
- □ Lecture notes/book
- □ One A4 sheet of annotations
- □ Dictionar(y)(ies). If yes, please specify:

Important:

- examinees are only permitted to visit the toilets under supervision
- it is not permitted to leave the examination room within 15 minutes of the start and within the final 15 minutes of the examination, unless stated otherwise
- examination scripts (fully completed examination paper, stating name, student number, etc.) must always be handed in
- the house rules must be observed during the examination
- the instructions of examiners and invigilators must be followed
- no pencil cases are permitted on desks
- examinees are not permitted to share examination aids or lend them to each other

During written examinations, the following actions will in any case be deemed to constitute fraud or attempted fraud:

- using another person's proof of identity/campus card (student identity card)
- having a mobile telephone or any other type of media-carrying device on your desk or in your clothes
- using, or attempting to use, unauthorized resources and aids, such as the internet, a mobile telephone, etc.
- using a clicker that does not belong to you
- having any paper at hand other than that provided by TU/e, unless stated otherwise
- visiting the toilet (or going outside) without permission or supervision

Exam 3DEX1: Physics of new energy
26-1-2016 van 9:00-12:00

PLEASE READ THESE INSTRUCTIONS FIRST!

Solve each exercise on a separate sheet of paper, and make sure they all have your name on it!

In this exam we would like to summarize with you the issues discussed in this class by 4 exercises:

1. Energy in general: the energy problem, consumption and storage.
2. Thermodynamics: how thermodynamics imposes a limit on the maximum efficiency to convert heat into work.
3. Fusion power: the basic principles and its challenges to realise a fusion power plant
4. Solar cells: its structure and the operating principle

All four questions are posed in English. You can choose yourself to answer in either English or Dutch. We also provide an indicative time needed to complete the exercise (just our own estimate, maybe it helps you to check whether your pace is sufficient).

For each of the sub questions the number of points that can be scored is indicated. The total number of points is 100. The final result F is calculated according to F= 1.0 + 0.09 x (number of points score) and rounded to 1 decimal.

The use of calculators is allowed, but any other books, phones, laptops, internet access, formulary is strictly prohibited.

Below you find some constants, which you might need for solving some exercises. (Note that you do not necessarily need all of them, it is just a standard list).

Constants

e =	electron charge	=	1.6×10^{-19}	C
m_e =	electron mass	=	9.1×10^{-31}	kg
m_p	proton mass	=	1.67×10^{-27}	kg
c =	speed of light	=	2.99×10^{8}	m/s
ε_0 =	vacuum permittivity	=	8.85×10^{-12}	F/m
μ_0 =	magnetic permeability	=	1.26×10^{-6}	Vs/Am
h =	Planck constant	=	6.63×10^{-34}	Js
k_B =	Boltzmann constant	=	1.38×10^{-23}	J/K
g =	gravitation of Earth	=	9.81	m/s^2
N_A =	Avogadro's number	=	6.02×10^{23}	mol^{-1}
R =	Gas constant	=	8.31	J/(mol K) (= 8.31 Pa m^3/(mol K))
atm =	atmosphere	=	1.01×10^{5}	Pa
ρ_{air} =	density of air	=	1.3	kg/m^3
ρ_{water} =	density of water	=	1000	kg/m^3
k_w=	thermal conductivity wood	=	0.1	W/(m K)
k_r =	heat conductivity rubber	=	0.15	W/(m K)

atomic mass (amu): hydrogen=1 , helium=4, carbon=12, oxygen=16

1. **Energy – General – 15 pts – estimated time: 25 minutes**

a) [5 pts] *Energy Problem:* What are the three main factors determining the energy problem which we will face in the near future? Give one solution to this. In which way can science contribute to this? Provide one example.

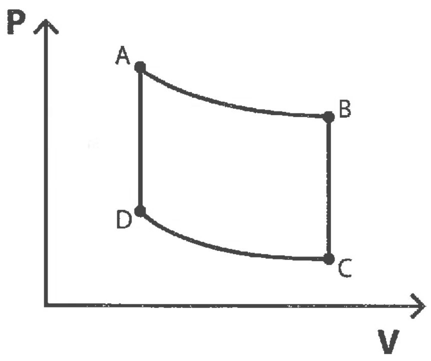
b) [5 pts] *Energy Use:* The largest energy consumption by households is for transport (cars) and heating. Let's have a look at the latter one. What is the most efficient energy use for cooking: an electrical cooking plate or a gas cooker (gas stove). Why? Calculate the power needed to raise the temperature of a 5 litre pan filled with water from 5 °C to 100° C (the boiling temperature) in 3 minutes. What is the price for this if it is done electrically (25 ct/kWh, 40 % efficiency)?

c) [5 pts] *Energy storage:* In an electric car the energy is stored in a battery. Typically this car can drive only 100 km on full electric energy, whereas a conventional car on petrol can drive easily 500 km on a single tank. What is the essential difference in the energy storage?
How is this different for fuel cells based on hydrogen? Explain.

2. **Thermodynamics – 15 pts – estimated time: 25 minutes**

Two moles of an ideal mono-atomic gas (c_V= 12.47 J/(mol·K), c_p=20.78 J/(mol·K)) follow a thermodynamic cycle according to the path D→A→B→C→D. The steps DA en BC are isochoric. The steps AB and CD are isothermal. In state D, the pressure is $2 \cdot 10^5$ Pa and the temperature is 360 K. In state B, the volume is $V_B=3V_D$ and the pressure is $P_B=2P_C$.

a) [2 pts] Draw the PV diagram for the cycle DABCD.
b) [8 pts] Calculate the work and the heat for each step of the cycle.
c) [5 pts] Calculate the efficiency of the cyclic process.



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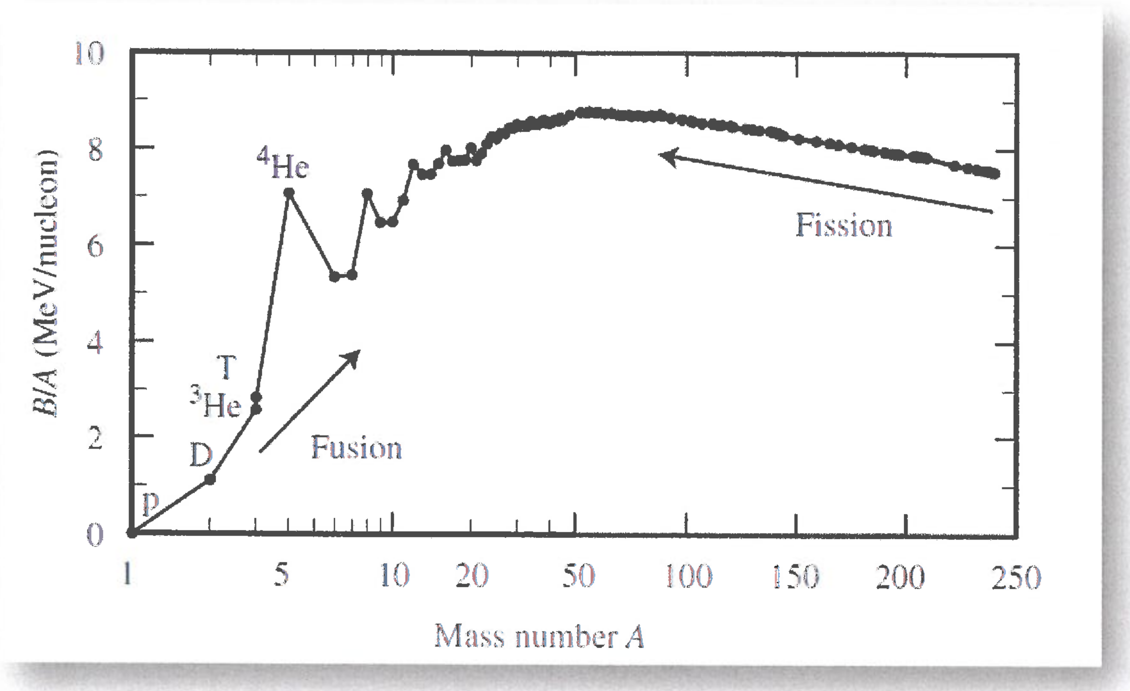
3. **Fusion – 35 pts – estimated time 50 minutes**

Fusion Energy is a very promising new energy source:

- The fuel is abundantly present for thousands of years
- No CO_2 emission
- Inherent safe
- Large scale

Nevertheless, we still do not have a working fusion reactor yet. Before this will be realised many challenges have to be overcome. Let's have a closer look at a few of those.

a) (6 pts) Challenge 1: The fuel: the easiest fusion reaction is the one between deuterium and tritium nuclei. However, in a plasma mix of deuterium and tritium also other fusion reactions are possible. Give at least two other reactions that will occur in this plasma and use the picture below to estimate the amount of energy released in this reaction.



b) (3 pts) Challenge 2: The Burn Condition. To have net fusion power we need to fulfil the following condition: More power should be produced by fusion reactions than we need to provide to heat the plasma. This leads to the fusion triple product. Which are the three parameters which determine this condition?

c) (7 pts) Challenge 3: Magnetic confinement. We need to confine the hot plasma with a magnetic field B of 5T.

- (2 pt) calculate the average speed of a deuterium ion in a 15 keV plasma
- (2pt) calculate the radius at which this ion gyrates around the magnetic field

4. **Solar Cells – 35 pts – estimated time 50 minutes**

Analyse and carefully describe in your own words the structure of a crystalline silicon solar cell by addressing the following questions:

a) (4 pts) Make a complete sketch of a c-Si solar cell and indicate its components.

b) (3 pts) The p-n junction in a solar cell is essential because it takes care of the separation of the electrons and holes, once they have been generated by sunlight absorption in the semiconductor. Make an accurate sketch of the energy band diagram of a p-n junction in a solar cell and indicate in which directions the electrons and holes will be transported when they experience the electric field of the junction.

c) (6 pts) Explain why it is not possible to convert all the photocurrent (i.e. all the photo-generated charges) in useful electrical current from a solar cell. Make use of the electrical circuit of a solar cell.

d) (4 pts) According to the Matlab simulation, a crystalline silicon (c-Si) wafer with a thickness of just 200-250 μm is sufficient to quantitatively absorb the solar light. However, this is in discrepancy with the value of the penetration depth of the sunlight into c-Si, which suggests that we would need at least a thickness of 1000 μm to take advantage of all photons with energy above the c-Si band-gap (1.1 eV). Can you explain this discrepancy by taking into consideration the structure of the solar cell?

e) (5 pts) The efficiency of the sunlight-to-electricity conversion process is limited by the 2nd law of thermodynamics. Why? Furthermore, provide an estimate of the thermodynamic limit values, according to the two models which we described during classes. Why do the two models provide different thermodynamic efficiency values?

f) (8 pts) Provide a list of all loss mechanisms occurring in a commercial solar cell and explain them in detail by making use of sketches.

g) (5 pts) Which is the major loss mechanism? Can you provide and explain in detail one approach to address this specific loss mechanism? Make also use of a sketch to present your approach.

line.

- (3pt) Sketch the motion of this ion in the following three situations: the ion is moving parallel to the magnetic field, perpendicular to the magnetic field and oblique (i.e. under an angle) to the magnetic field. Indicate clearly the directions of magnetic field and velocity.

d) (4 pts) Challenge 4: Temperature. Fusion of the D-T reaction is easiest at 15 keV (equal to approximately 165 Million K). This can be done by either injecting particles or injecting electromagnetic waves
   - (2 pts) Which particles are best to inject to best to inject to heat the plasma. Explain this heating principle in 2-3 sentences.
   - (2 pts) To heat the deuterium nuclei in the plasma, which frequency of electromagnetic wave is best to inject in a reactor with a magnetic field of 5T?

e) (7 pts) Challenge 5: Wall power load. The aim of a fusion power plant is to produce electricity. Assume we have a fusion power reactor of the type tokamak, producing 4 GW of fusion power (from the D-T reaction). The major radius is 6 meter, the minor radius = 2 meter. Assume the torus has a circular cross-section.
   - (2pt) Describe how this fusion power is converted to electricity and give a coarse estimate of the electric output power of this reactor.
   - (3pt) The fusion power is distributed between the neutrons and the alpha particles. Let's concentrate on the neutrons. What is the power of these neutrons? Where is it deposited? Besides power production, what other use do the neutrons have?
   - (2pt) Calculate the power wall load (in MW/m^2) as a result of the neutrons.

f) (4 pts) Challenge 6: control. To control the plasma we need to measure in real time some plasma parameters, like the plasma temperature.
   - (2pt) Describe a measurement technique (physics principle) to do this.
   - (2pt) Use a sketch to illustrate this and indicate the main hardware component.

g) (4 pts) Challenge 7: Fusion is only competitive with alternative energy sources if the costs/ kWh are comparable. A fusion reactor is extremely expensive (about 10 Billion Euro's) because of the infrastructure.
   - (2 pt) Give one argument why the costs/kWh can still be reasonable
   - (2 pt) Also give an argument why the costs/kWh are at risk of rising too high (assume that we will be able to reach the required fusion criterion to produce net energy).