Teacher's manual

v.1.0

General introduction

Energy plays a fundamental role in our modern society. With the increasing growth of technologies and of the number of users of all these technologies, the world's energy demands are estimated to increase continuously. If we should continue the processes of generating energy than eventually the demand will be higher than we could possibly offer. Therefore, this series of lessons will provide insight to a possible future energy solution: nuclear fusion.

This lesson series start with module 1 *Fusion basics*, which will give the students the basics for all the other modules. **Therefore module 4 *Materials for Fusion* can be used when the content of module 1 has been introduced.**

This series of lessons is intended for pre-university education: level ISCED 3-4.

Using the modules

The student readers consist of different lesson materials: the bright coloured boxes, which are called 'aside', will provide extra explanations of the underlying topics. These are optional to use in the classroom.

The light-coloured boxes provide classroom exercises. These can be used during class for further discussion and can serve as a check to see if the students understand the material.

The full content of a module consists of:

- A student reader
    - Including some classroom exercises
- Additional exercises
- A PowerPoint presentation
    - Including classroom exercises with answers
- Teacher manual
    - Including the following appendices
        - Table of constants and conversion factors
        - Answers to the classroom exercises
        - Answers to the additional exercises

- EXTRA: Module 4 also features a separate Annex covering superconductivity in fusion. This is a short extension of the student reader of the module that can be used to discuss the phenomenon of superconductivity and its uses in fusion research.

Content of the teacher manual

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Chapter 1: Learning objectives

At the end of this module, students are able to:

- Identify the fundamental parts of a standard fusion device.
- Understand the choice of materials for different parts of a fusion reactor.
- Understand the challenges of heat exhaust and neutron irradiation.
- Understand the need and the issues related to plasma facing components.
- Name the different requirements that plasma-facing materials need to satisfy.
- Explain the effect of neutron irradiation on materials.
- Explain the different functions of the blanket.
- Understand the need of a cooling systems.

Chapter 2: Closely related subjects or lessons

Next to the concepts discussed in module 1, the following subjects are closely related:

- Fundamental parts of a fusion device (the tokamak)
- Materials for different parts
- Materials science
- Atomic physics
- The role of neutrons produced by fusion reactions
- Electricity
- Magnetism

Chapter 3: Topics of Module 4

For each chapter the corresponding physical topics are given. This can be used to adapt the lesson plan corresponding to the knowledge of the students and the needed time in class.

1. **Introduction to the tokamak parts and extreme conditions**
    - Essential parts of a fusion reactor (tokamak)
        - Inner reactor walls
            - First wall
            - Divertor
        - Blanket
        - Superconducting magnets
2. **The heat exhaust problem and plasma-facing materials**
    - The need for a heat exhaust
    - The challenge of the divertor heat load
        - Heat shields
        - Material requirement for Plasma-facing components
        - Material options
3. **Neutron Irradiation**
    - Microscopic effects
    - Macroscopic effects
    - Neutron hard materials

4. The Blanket and its materials
  - The upside of neutrons
  - Blanket overview
    - Tritium breeding
    - Heat exchanging
    - Neutron stopping

Chapter 4: Brief summary of module 4

Module one gives an introduction to the working principle of the tokamak, the doughnut-shaped fusion device and how fusion reactions in the plasma generate energy. Module four focuses on the tokamak and how the energy travels inside it to be converted into electricity. Module four discusses the fundamental parts of the tokamak and the related material challenges.

Chapter one gives an introduction to the extreme conditions encountered inside a tokamak introducing its essential parts: the inner reactor walls, the blanket and the superconducting magnets.

Chapter two focuses on the heat exhaust challenge. Understanding why and how the tremendous energy generated by fusion reactions is a problem for the internal reactor wall is crucial. For this, correctly figuring out how, even if we confine the plasma with magnetic fields, energy travels in the form of heat to the plasma-facing components of the reactor is essential. The knowledge from module 1 related to fusion reaction and magnetic confinement is used to explain why the components of the inner reactor walls of a tokamak need to be heat shields. The geometry and the complex requirements these heat shields must satisfy are introduced. The material options for plasma-facing components are described. The material choice for ITER is presented and explained with visuals of the inside of the reactor.

Chapter three starts with a general overview of the issues related to the neutrons produced by fusion reactions. The various problems concern the reactor materials subjected to an actual bombardment of neutrons that consequently undergo degradation. Chapter three describes the microscopic nature of the degradation and its macroscopic consequences on the material properties. An insight into how such problems can be solved is provided with an example.

As opposed to the previous one, **chapter four** starts with the upside of neutrons and a general overview of the blanket. In a tokamak, the blanket functions are all related to the downsides and upsides associated with neutrons. Chapter four finally describes the three fundamental functions of the blanket.

Finally, the module concludes with further reading advice and mentions the Superconductivity Annex. This is a complementary section devoted to superconductivity and superconducting materials.

Chapter 5: Basic lesson schemes

Like in the first module there are two basic lesson schemes for direct use for a short class (15 minutes) and a longer class (1 hour). For this module there is a difference for teaching average and advanced students.

The goal of this lesson schemes is to give an idea of a lesson and to decrease the preparation for the teacher. Feel free to adapt the scheme to your own lesson plan. For both lesson schemes the student activities, preparation and classroom ideas are the same.

The student activities involve listening, discussing, asking questions and working on the exercises.

Note that in the lesson schemes below, the mentioned classroom exercises are available in the PowerPoint presentation for Module 4 and in the student reader with the same numbering (only the exercise 4.0 features only in the powerpoint presentation!)

Preparation for these lessons involves:

- Downloading the PowerPoint
- Making the student reader and additional exercises available for students

15-min lesson for average students

This lesson has two goals: first, to introduce the fundamental parts of a tokamak, and second, to pinpoint the two most pressing and exciting material engineering challenges that fusion scientists must face. The classroom exercises for the students to work in class are quick.

Remember that the ultimate scope is always to create enthusiasm and curiosity by stimulating the reasoning skills of the students with fusion engineering concepts and visuals.

The materials needed for this lesson are:

- The student reader
- The PowerPoint presentation of Module 4

Preparation for this lesson involves:

- Make a copy of the PowerPoint presentation with only the selected slides
- Making the student reader available for students.

Duration	Teacher activity	Materials	Student activity
3 min	Introduction: tokamak parts	Chapter 1: PowerPoint slide: 2 → 6	Listen, ask questions
2 min	Presenting chapter 2: **Heat exhaust and plasma-facing components**	Chapter 2: PowerPoint slide 9 and 10	Listen, ask questions
3 min	Classroom exercise 4.0. Present and explain the answers.	Chapter 2: PowerPoint slide 10 → 11	Work in pairs on the classroom exercise. Discuss!
5 min	Presenting chapter 3: **Neutron irradiation and Blanket Materials**	Chapter 3 and 4: PowerPoint slide 20, 21, 29	Listen, ask questions
3 min	Classroom exercise 4.3. Present and explain the answers.	Chapter 3: PowerPoint slide 25 → 27	Work in pairs on the classroom exercise. Listen, ask questions and discuss

15-20 min lesson for advanced students

This lesson has two goals: first, to introduce the fundamental parts of a tokamak, and second, to pinpoint the two most pressing and exciting material engineering challenges that fusion scientists must face. The classroom exercises for the advanced students lesson are lengthier and require more reasoning and/or calculations.

Remember that the ultimate scope is always to create enthusiasm and curiosity stimulating the reasoning skills of the students with fusion engineering concepts, visuals, and calculations.

The materials needed for this lesson are:

- The student reader
- The PowerPoint presentation of Module 4

Preparation for this lesson involves:

- Make a copy of the PowerPoint presentation with only the selected slides
- Making the student reader available for students.

***Note that the classroom exercise 4.0 is only present in the PowerPoint presentation (not in the student reader).**

Duration	Teacher activity	Materials	Student activity
3 min	Introduction: tokamak parts	Chapter 1: PowerPoint slide: 2 → 6	Listen, ask questions
2 min	Presenting chapter 2: **Heat exhaust and plasma-facing components**	Chapter 2: PowerPoint slide 7 and 9	Listen, ask questions
3-5 min	Classroom exercise 4.0 and 4.1. Present and explain the answers.	Chapter 2: PowerPoint slide 10 → 13	Work in pairs on the classroom exercise. Discuss!
5 min	Presenting chapter 3 and 4: **Neutron irradiation and Blanket Materials**	Chapter 3 and 4: PowerPoint slide 19 → 21, 29	Listen, ask questions
3-5 min	Classroom exercise 4.3 and 4.5. Present and explain the answers.	Chapter 3: PowerPoint slide 25 → 27 and 34 → 35	Work in pairs on the classroom exercise. Listen, ask questions and discuss
			Make at home: Classroom exercise 4.2 and 4.4

1-hour lesson for average students

The goals, preparation and materials needed for the 1-hour lesson are the same as for the shorter lesson: first, to introduce the fundamental parts of a tokamak, and second, to pinpoint the two most pressing and exciting material engineering challenges that fusion scientists must face, to create enthusiasm and curiosity and to stimulate the reasoning skills of the students.

This 1-hour lesson aims at introducing the concepts more in-depth giving more details and letting the student discuss and solve the exercises first alone, then with an open discussion.

The materials needed for this lesson are:

- The student reader
- The PowerPoint

Preparation for this lesson involves:

- Make a copy of the PowerPoint presentation with the selected slides
- Making the student reader available for students.

***Note that the classroom exercise 4.0 is only present in the PowerPoint presentation (not in the student reader).**

Duration **(~1h)**	Teacher activity	Materials	Student activity
5 min	Introduction: tokamak parts	Chapter 1: PowerPoint slides: 2 → 6	Listen, ask questions
5 min	Introduce chapter 2: **Heat exhaust and plasma-facing components**	Chapter 2: PowerPoint slides 7 → 9	Listen, ask questions
~8 min	Classroom exercises 4.0 and 4.1	Chapter 2: PowerPoint slides 11 → 14	Work alone for 4 minutes on the classroom exercise. Then, open discussion with the entire class!
5 min	Introduce other requirements for plasma-facing components and ITER material choices	Chapter 2: PowerPoint slides 14, 17-18	Listen, ask questions
~8 min	Classroom exercise 4.2.	Chapter 2: PowerPoint slides 15 → 16	Work alone for 4 minutes on the classroom exercise. Then, open discussion with the entire class!
10 min	Presenting chapter 3: **Neutron irradiation**	Chapter 3: PowerPoint slides 19 → 24	Listen, ask questions
5 min	Classroom exercise 4.4. Present and explain the answers.	Chapter 3: PowerPoint slides 25 → 27	Work alone for 2 minutes on the classroom exercise. Then, open discussion with the entire class!
10 min	Presenting chapter 4: **Blanket Materials**	Chapter 4: PowerPoint slides 29→ 31	Listen, ask questions
5 min	Classroom exercises 4.3, 4.4	Chapter 4: PowerPoint slides 32→ 35	Open discussion

1-hour lesson for advanced students

The goals, preparation and materials needed for the 1-hour lesson for advanced students are the same as for the 1-hour lesson for average students. As such, this lesson has two goals: first, to introduce the fundamental parts of a tokamak, and second, to pinpoint the two most pressing and exciting material engineering challenges that fusion scientists must face.

Remember that the ultimate scope is always to create enthusiasm and curiosity stimulating the reasoning skills of the students with fusion engineering concepts, visuals, and calculations.

The materials needed for this lesson are:

- The student reader
- The PowerPoint presentation

If the students already know the topics, or if the students have demonstrated to be quite interested and skilled in reasoning and/or calculating, then a reversed classroom setting can be created, where the role of teacher and students are switched in the classroom. The teacher only asks questions, and the students have to explain the topics. The suggestion for the advanced lesson is to tease the student with the classroom exercises and let them discuss with each other if they disagree. The classroom exercises can be used for students to get a taste of the topic before the teacher's actual presentation of the chapter.

Duration **(~1h)**	Teacher activity	Materials	Student activity
5 min	Introduction: tokamak parts	Chapter 1: PowerPoint slides: 2 → 6	Listen, ask questions
8 min	Introduce and let student discuss **Classroom exercises 4.0 and 4.1**	Chapter 2: PowerPoint slides 10 → 13	Work alone for 4 minutes on the classroom exercise. Then, open discussion classroom/group of 4
5 min	Introduce chapter 2: **Heat exhaust and plasma-facing components**	Chapter 2: PowerPoint slides 7 and 9	Listen, ask questions
8 min	Introduce and let student discuss **Classroom exercise 4.2.**	Chapter 2: PowerPoint slides 15 → 16	Work alone for 4 minutes on the classroom exercise. Then, open discussion classroom/group of 4
5 min	Present the other requirements for plasma-facing components and ITER material choices	Chapter 2: Power Point slides 14, 17, 18	Listen, ask questions
5 min	Present the topic of **neutron irradiation** and introduce Classroom exercise 4.3. a)	Chapter 3: PowerPoint slides 25 → 27	Work alone for 2 minutes on the classroom exercise. Then, open discussion classroom/group of 4
10 min	Present chapter 3: **Neutron irradiation**	Chapter 3: PowerPoint slides 20 → 28	Listen, ask questions

5 min	Classroom exercise 4.3. Present and explain the answers.	Chapter 3: PowerPoint slide 25 → 27	Work alone for 2 minutes on the classroom exercise. Then, open discussion with the entire class!
5 min	Introduce the blanket and let student discuss **Classroom exercises 4.5**	Chapter 4: PowerPoint slide 29, 35,36	Open discussion
10 min	Presenting chapter 4: **Blanket Materials**	Chapter 4: PowerPoint slide 29→ 32	Listen, ask questions

Chapter 6: use of PowerPoint and other materials

There is a PowerPoint (for each module) available at the site:
https://fusenet.eu/education/material.

The PowerPoint consists of the whole module, including the classroom exercises and answers, and can be used directly in class. For an overview of extra material see chapter 7. You can adapt the PowerPoint to the topics which are treated in the classroom.

To introduce the different topics of module 4, it is possible to give the students a preparation exercise at home per topic. This could be one or more of the exercises.
For the preparation also some subjects from 'further references for study and fun' can be used. See chapter 7.

Chapter 7: Further references for study and fun for module 4

For teachers
The following contains general background information (in English) for teachers of this module. This is merely intended to use for your own knowledge and understanding of the subject. It is possible to use this content in the classroom but then it has to be adapted to the level of the students.
Some sites will give information about the topics covered or related to this module. Under each URL there is a short introduction of what can be found.

- FuseNet website - https://www.fusenet.eu/education/material Here you can find the other four modules. Furthermore, there are also theoretical papers, courses and experiments of topics related to this lesson series.

For Teachers and students
At the end of the module, you can find further reading material. The material in this chapter can be used as an extra explanation for the students in class. Some URLs give a more in-depth look on the different topics or give an example of an experiment. After each URL information will be provided about the content and possible use.

Appendix A: table of constants

Quantity	**Quantity**	**Conversion factor to SI units**
Energy[1]	1 Calorie	4.184 J
Energy[3]	1 toe*	$4.2 * 10^{10}$ J
Energy[1]	1 kWh*	$3.6 * 10^{6}$ J
Mass[1]	1 Ton	$1.0 * 10^{3}$ kg
Mass [1]	1 amu/u/ame	$1.66 * 10^{-27}$ kg
Temperature[1]	0 °C	273.15 K
Pressure[1]	1 bar	$1.0 * 10^{5}$ Pa

Table A.1 conversion factors

Quantity	
Core temperature Sun[2]	$1.571*10^{7}$ K
Surface temperature Sun[1]	5780 K
(mean) Density Sun[2]	1408 kg/m^3
Core density[2]	$1.622*10^{5}$ kg/m^3
Core pressure Sun[2]	$2.477*10^{11}$ bar
Surface temperature Earth[1]	295 K
(mean) Density Earth[2]	5514 kg/m^3
Mass electron[1]	$9.109 *10^{-31}$ kg
Charge electron[1]	$1.602*10^{-19}$ C
Mass proton[1]	$1.673*10^{-27}$ kg
Charge proton[1]	$1.602*10^{-19}$ C
Mass neutron[1]	$1.675*10^{-27}$ kg

Table A.2 constants

[1] Noordhoff uitgevers & NVON (2021). *Binas HAVO/VWO Informatieboek 6de editie (6e havo/vwo)* (01 ed.). Groningen, Nederland: Noordhoff Uitgevers.

[2] Sun Fact Sheet. (2018). Retrieved 13 July 2021, from https://nssdc.gsfc.nasa.gov/planetary/factsheet/sunfact.html

[3] IEA Unit converter and glossary, for common energy units. From https://www.iea.org/reports/unit-converter-and-glossary

Appendix B: Solution to the classroom exercises

Classroom exercise 4.0

Tokamak devices use magnetic field to keep the hot plasma confined and safely detached from the internal reactor walls. Give at least one reason why a heat exhaust is necessary for a commercial fusion reactor.

To prevent melting, but also to remove helium ashes from the reactor (see also page 6 of the student reader)

Classroom exercise 4.1

The thermal heat load to the divertor in ITER is estimated to be $10\,\frac{\text{MW}}{\text{m}^2}$. But how much is that? Compare it with the maximum energy that is generated using a thermal lance, which 'burns' iron with a heat of combustion of $4.23\,\frac{\text{KJ}}{\text{g}}$.

(a) What is the energy generated with a standard thermal lance if it combusts a charge of 3 grams of iron?

$$\left(4.23\frac{KJ}{g}\cdot 3g \;\approx 12KJ\right)$$

(b) How much energy hits a surface of $1\ \text{m}^2$ of divertor material in just one millisecond of exposure to the thermal heat load of ITER?

(c) $$\left(10\ \cdot\frac{10^6 J}{s\cdot m^2}\cdot 0.001s\ \cdot 1m^2 \approx 10\ KJ\right)$$

How do they compare? And knowing that a thermal lance can be used to cut through the kind of steel that banks trust to hold their property safe, what does this tell you about the requirements for the divertor?

(In just one millisecond, a square meter of divertor gets almost the same amount of energy that an entire thermal lance charge can produce. It is a lot! The temperature of the divertor material will rise a lot → To avoid melting, the material must 1) have a high melting point and 2) be a good heat conductor to drive all this heat away without warming too much.)

Classroom exercise 4.2

In classroom exercise 4.1 we did some heat load calculations. In this follow-up, we ask ourselves the question: what material can resist such a high heat load without melting? Is some active cooling necessary to keep the material below its melting point? To calculate the temperature, we can approximate the divertor as a perfect black body. A black body radiates (emits power) according to the Stefan-Boltzmann Law:

$$P = \frac{\Delta E}{\Delta t} = \sigma_B A T^4$$

Here, P is the emitted power in watt, $\sigma_B = 5{,}67 \times 10^{-8} \frac{J}{s \times m^2 \times K^4}$ the Stefan-Boltzmann constant, A the surface area of the black body and T the surface temperature. Now, suppose that you have a divertor of $1\mathrm{m}^2$ and assume that all the $\frac{10\mathrm{MW}}{\mathrm{m}^2}$ are radiated away.

What is the surface temperature?

a)

$$\left(T = \left(\frac{10\left[\frac{MW}{m2}\right]}{\sigma_B A} \right)^{\frac{1}{4}} = \left(\frac{1015}{5.67} \right)^{\frac{1}{4}} = \sim 3650K = 3923{,}15\,°C \right)$$

b) How does this compare to the melting* temperature of the following materials?

Tungsten ***(3.422 °C)*** Iron ***(1538 °C)*** Carbon* ***(3643°C)*** Beryllium ***(1287 °C)***

c) What do you conclude about cooling? Can the material radiate away all heat and thus remain cool enough by itself (passively) or is additional active cooling required? And why?

(No material can radiate away such high power without melting! Active cooling is necessary! We need to actively remove the heat from the material via a cooling system. For that we need materials with optimal heat conduction properties!)

Classroom exercise 4.3

a) List three different macroscopic detrimental effects on materials due to neutron irradiation.
(Swelling, hardening embrittlement, see slide 22 of the presentation)

b) You just learned what swelling is, but why do you think swelling is a problem for plasma-facing or blanket components? Can you give an example?

(Swelling causes mechanical assembly issues! Swelling causes the components of the internal walls or of the blanket to break more easily! See slide 27 of the presentation)

Classroom exercise 4.4

In a reactor, the blanket needs to be heavily and actively cooled. Why?

(Because neutrons, colliding with the atoms of the materials, heat up the components of the blanket. We want to use that heat to produce electricity, so we need to actively cool the blanket)

Classroom exercise 4.5

In a tokamak, what are the most important functions of the blanket?

(Tritium Breeding, Heat exchanging, neutron stopping; see slides 29-31 of the presentation)