Nuclear Fusion

Contents: A structured discussion on the possibility of using nuclear fusion to generate electricity.

Time: Homework plus 1 double period.

Intended use: GCSE Physics, Chemistry or Science. Most likely to be of use at the end of a GCSE course, in the fifth year, and could also be used at sixth-form level. Links with work on nuclear structure, radioactivity, nuclear fission, generation of electricity and energy sources.

Aims:

- To complement and revise prior work on atomic structure, radioactivity and energy supply
- To introduce the principles of nuclear fusion, and its use in the generation of electricity
- To develop an informed awareness of some of the issues concerned with nuclear fusion
- To promote an awareness of the value of working with other countries
- To provide an opportunity to practise communication skills and to encourage students to enter into discussion.

Requirements:
For each member of the class:
1 copy of the Introduction (Sheet I)
1 copy of the General Briefing (Sheets GB)
1 copy of the Test (Sheet T)

For each group of five students:
1 copy of each of the Expert's Briefing Sheets (Sheets EB1, EB2, EB3, EB4)
1 copy of the Chairperson's Briefing Sheets (Sheets CB)

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This structured discussion is intended to give a factual introduction to the generation of electricity from nuclear fusion and to help students weigh up some of the issues related to nuclear fusion. It is designed for use after they have studied the atomic nucleus and nuclear energy. The General Briefing is no more than a condensed summary. The teacher may well want to go through the material covered in the General Briefing with the class before starting the discussion.

Procedure

1. Give each student a copy of the General Briefing. Allow time to read and study it — this is best done for homework preceding the lesson.
2. Get students to do the test. This should take no more than 15 minutes. Go through the answers.
3. Form the class into groups of five. Each group should have a Chairperson, chosen for his or her potential for leading a discussion. If the class does not divide neatly into groups of five, have some groups of six.
4. Give the Chairpersons their Briefing Sheets (CB). Give Expert's Briefing Sheets (EB1, EB2, EB3, EB4) to the other four members of each group — a different briefing to each member in a group. If any groups have six members, EB1 could be given to two people. Allow them time to study the sheets before beginning the discussion. If the timing of lessons permits, it is most effective if students are able to study their briefings beforehand, perhaps for homework.

Other resources

The United Kingdom Atomic Energy Authority produce a wide range of resources, many of them free. They include leaflets, booklets, posters, audio-visual packs and films. Naturally, these materials put the case in favour of nuclear power.

UK Atomic Energy Authority
Information Services Branch
11 Charles II Street
London SW1Y 4QP

Particular information on fusion research can obtained from:

The Information Centre
UKAEA
Culham Laboratory
Abingdon
Oxon OX14 3DE

Acknowledgements Figure 1 (Sheet I) and Figure 2 (EB1)/Figure 1 (EB2) from material supplied by United Kingdom Atomic Energy Authority; Figure 3 (GB) reproduced as line drawing by courtesy of UKAEA Culham Laboratory; Figure 1 (EB4) from diagram in W.Häfele, et al., *Fusion and Fast Breeder Reactors* (International Institute for Applied Systems Analysis).

NUCLEAR FUSION

Introduction

In power stations the generators are run by turbines. Energy is needed to produce high pressure steam which drives the turbines. The energy often comes from burning fuels such as coal or oil.

In nuclear power stations the energy comes from fission (splitting) of uranium atoms. In the future the energy may come from nuclear fusion (joining).

Here are some of the questions you will think about as you discuss the ideas in this unit.

- What will happen in about 100 years' time when oil and uranium have nearly run out?
- Can we get the energy we need from renewable sources such as the wind, the sun and waves?
- The sun and stars get their energy from nuclear fusion. Can we overcome the problems of controlling this source of energy on earth?
- Can fusion become a safe, clean and economic way of producing electricity?

Before starting you need to know some of the facts about nuclear fusion. First, you will be given a General Briefing. After studying this you will do a short test to check your understanding.

After that you will be working in a small group. You will discuss some of the questions and problems of using fusion power to generate electricity.

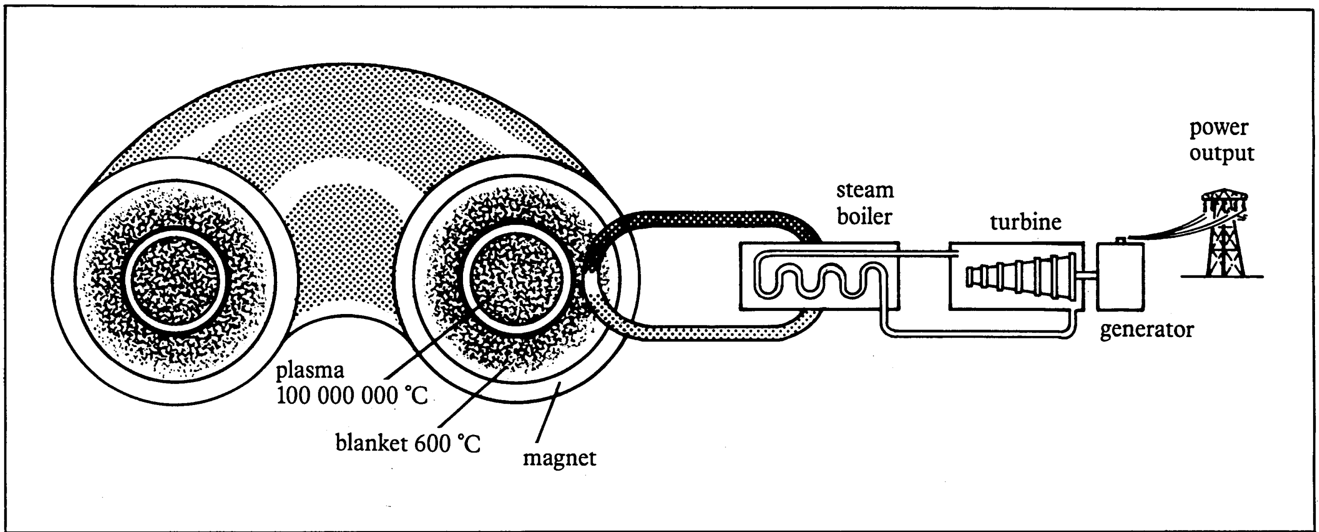


Figure 1 A diagram showing the main parts of a fusion power station

General Briefing

This is a summary of the theory of nuclear fusion.

What is nuclear fusion?

Nuclear fusion means joining together very light atoms. This is the opposite of what happens in normal nuclear power stations. They get their energy by splitting heavy atoms.

The energy of the sun comes from nuclear fusion. Can fusion be controlled? Can we make a small 'sun on earth' and use the energy to generate electricity?

Hydrogen atoms

Hydrogen atoms exist in three forms. Most hydrogen atoms have just one proton and one electron. Some hydrogen atoms have a neutron as well. This form of hydrogen is called deuterium. A third form has two neutrons and is called tritium.

Atoms which have the same number of protons and electrons but different numbers of neutrons are called **isotopes.** So there are three isotopes of hydrogen as shown in Figure 1.

Hydrogen and deuterium are not radioactive. Tritium is radioactive.

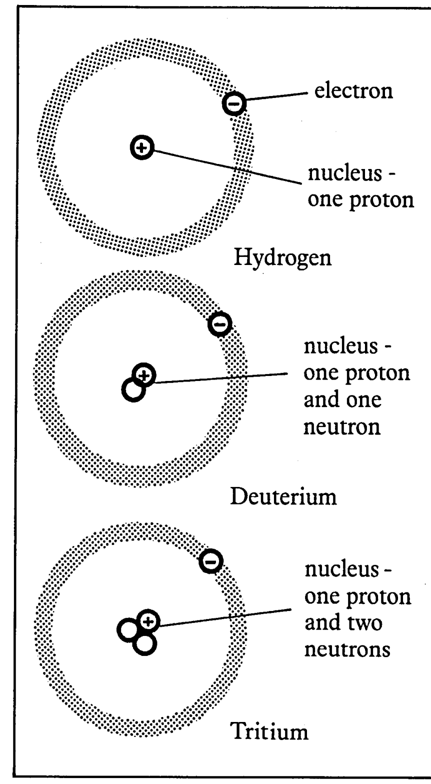


Figure 1 The three isotopes of hydrogen

Fusion Fuels

Deuterium and tritium are fuels for fusion reactors. A cubic metre of water contains 34 g of deuterium, so there is plenty of this fuel in the world — enough to supply fusion reactors for millions of years.

Tritium does not occur naturally in large quantities, so it has to be formed inside the reactor. Tritium can be formed in a fusion reactor by bombarding lithium with neutrons.

The problems of nuclear fusion

Fusion is the joining together of two **nuclei**. This is a much more difficult task than joining **atoms** together chemically.

There are big problems, but the reward is a supply of energy which will last practically for ever. Research towards a fusion reactor began in the late 1940s in Britain, America and the USSR. Since the early 1960s these countries and others have exchanged information. Progress has been made but we still do not know whether it is possible to make electricity commercially by nuclear fusion.

Fusion is difficult because the positive charges on the two nuclei repel each other. A big force is needed to push them together so that they join.

A temperature of 100 000 000°C is necessary for fusion reactions. At this temperature the atoms are moving fast enough. They have enough energy to overcome to repulsive force pushing them apart. They can get close enough to fuse (join).

Plasma

At the very high temperatures needed for fusion all gases become plasmas. The electrons and nuclei of the atoms separate. Because plasmas needed for fusion are so hot, they cannot be kept in an ordinary container. But plasmas can be contained in magnetic fields. A magnetic 'cage' can be made to hold them.

Energy from fusion

The idea of a fusion reactor goes like this. Deuterium and tritium fuse to form helium and high speed neutrons (Figure 2). Helium is not radioactive.

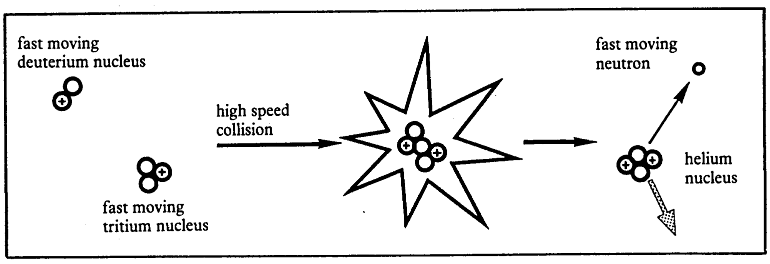


Figure 2 The process of nuclear fusion. In the plasma the atoms have lost their electrons. The nuclei have to collide fast enough to overcome the repulsion between the positive charges.

In a fusion reactor the neutrons are stopped by lithium atoms. The lithium is in the 'blanket' around the reactor. As the neutrons slow down their energy is transferred to heat water and turn it into steam. The steam is then used to generate electricity.

The tritium needed by the reactor is made as the lithium blanket is bombarded by neutrons.

Lithium and the materials used to make the reactor are not radioactive. However, the walls of the reactor become radioactive when they are bombarded by neutrons.

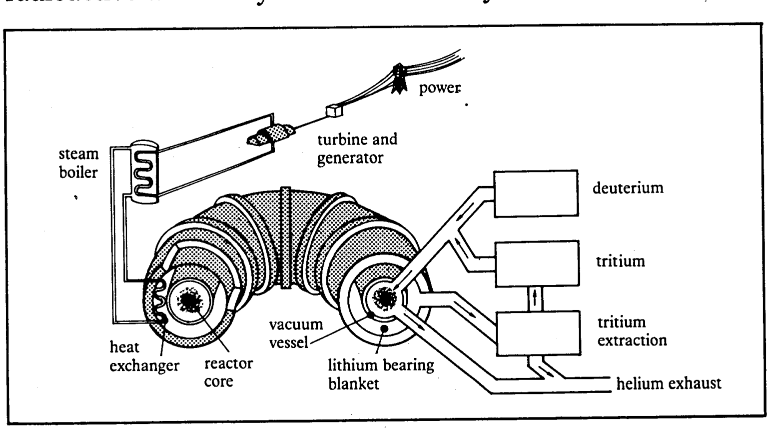


Figure 3 A scheme for a fusion reactor

Test on nuclear fusion

1 Which particles are found in the nucleus of an atom?

2 What is the difference between nuclear fission and nuclear fusion?

3 What are isotopes?

4 Where will the deuterium needed for fusion power come from?

5 Where will the tritium needed come from?

6 Why is a very high temperature needed for fusion?

7 What happens to the atoms when a gas becomes a plasma?

8 What job is done by the lithium blanket in a fusion reactor?

9 How will the energy from fusion be used to generate electricity?

10 Why are people now interested in the possibility of using nuclear fusion to generate electricity?

Expert's Briefing 1

The problem of containment

You will shortly be taking part in a group discussion on nuclear fusion. You are the only one in your group who has read this briefing, so you will be the expert on the problem of containment.

After you have read this, the Chairperson of your group will be asking the kinds of questions a 'man or woman in the street' might ask. Try to answer them as simply as possible, in your own words. Draw diagrams if it helps your answers. It is especially important that you understand and can explain the Tokomak system shown in Figure 2.

In nuclear fusion, nuclei in the plasmas react at very high temperatures. The 'problem of containment' is how to contain these plasmas for long enough to get energy out.

At temperatures of 100 000 000°C, ordinary containers would vaporize. However, plasma can be contained by magnetic fields. Scientists have investigated many different shapes of magnetic fields to find the best magnetic cage.

Fusion research started in universities around 1948 in apparatus no larger than a dinner plate. Gradually, larger devices were built, producing higher temperature plasmas for longer times. Different shapes of magnetic fields were studied. They led to the 'Tokamak system' first pioneered by scientists in the Soviet Union. In this system, plasmas are both heated and contained in a Tokamak.

The word Tokamak is Russian. It describes the shape of the plasma and the way it is contained.

In a Tokamak, plasma is heated in a doughnut shaped container, called a torus (Figure 1). It is heated by a large electric current produced by a transformer (Figure 2). The plasma is kept in place by the combination of two magnetic fields. One is produced by the plasma current and the second by the field coils.

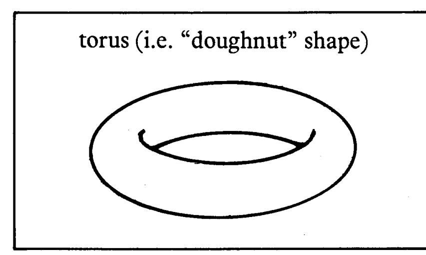


Figure 1 The torus

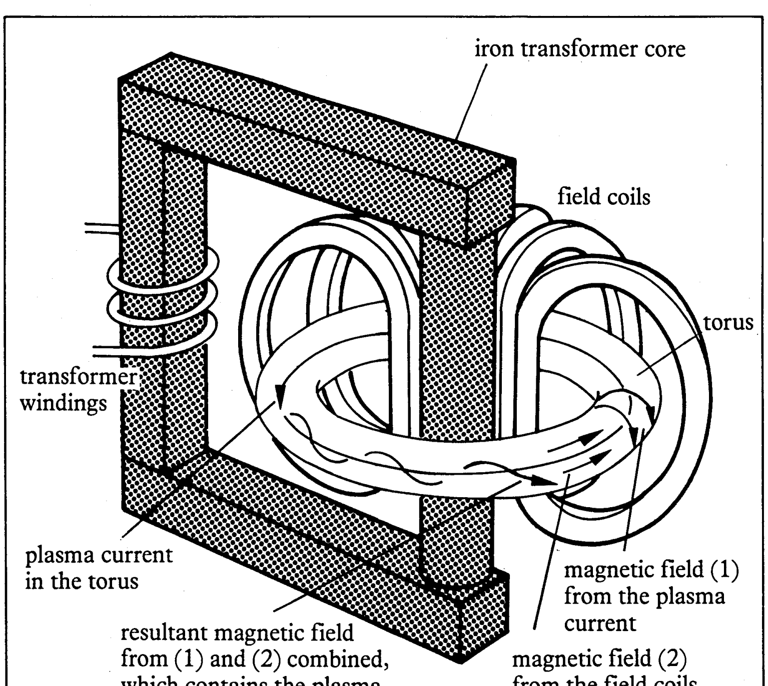


Figure 2 The Tokamak system

The magnetic 'cage' is able to keep in the plasma because the plasma is made up of charged particles (nuclei and electrons). As they move in the magnetic field, these charged particles experience a force which keeps them in place.

JET (The Joint European Torus)

JET is the largest Tokamak in the world. It is at Culham, near Oxford. JET is about 11.5 metres high and 15 metres in diameter.

The costs of JET are shared by the countries of the European Community together with Sweden and Switzerland. About half the team of scientists, engineers and administrators are British.

In the first three years of JET's experimental programme (1983-86) progress has been very impressive. Temperatures up to 140 000 000°C have been obtained in deuterium plasma. However, the containment of the plasma is not yet good enough for a working reactor. In the remaining five years of operation (1987-92) JET aims at getting the containment of plasmas closer to the conditions required in a reactor.

Expert's Briefing 2

Getting the conditions right

You will shortly be taking part in a group discussion on nuclear fusion. You are the only one in your group who has read this briefing, so you will be the expert on getting the conditions right in a fusion reactor.

After you have read this, the Chairperson of your group will be asking the kinds of questions a 'man or woman in the street' might ask. Try to answer them as simply as possible, in your own words. Draw diagrams if it helps your answers.

- A project called JET is a stage in a long research programme to find out whether fusion can be controlled as a source of energy.
- The second stage will be to develop the technology to show that the energy from fusion can produce electricity.
- The third stage will be to build an economical power station.

At the moment we are only at the first stage - trying to release controlled energy from fusion.

The three main problems

In order for fusion to happen, three conditions have to be met:

1 The temperature must be 100 000 000°C or more
2 The density of the plasma must be high enough
3 The plasma must be contained for a long enough time.

The big problem is to achieve all these conditions at the same time.

Heating the plasma

In the JET experiments, a transformer is used to produce a very large current flow in the plasma (Figure 1). The plasma is

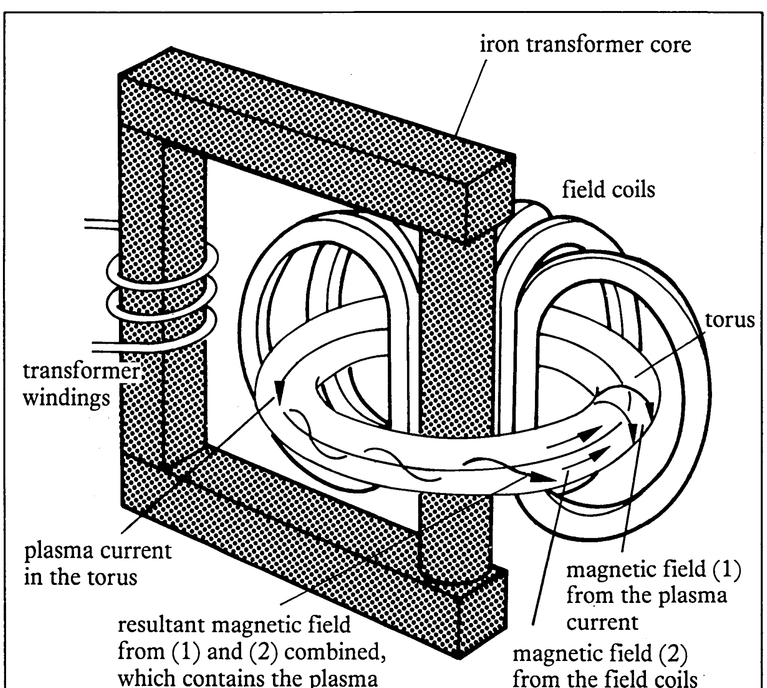


Figure 1

not a perfect conductor. In other words it has electrical resistance, and it heats up as the current flows. This is similar to the heating of an electric bar fire as a current flows through the heating wires. Unfortunately the plasma's resistance falls as it heats up. When the temperature reaches about 30 000 000°C it cannot be heated much more just by increasing the current.

Two extra methods of heating are used. One of these is to beam radiofrequency waves at the plasma. These waves are the right frequency to be absorbed by the plasma. This method works like a microwave cooker.

The second method is to bombard the plasma with high energy hydrogen or deuterium atoms. These fast atoms are fired in and they give their energy to the plasma.

Using all three heating methods it is possible to reach temperatures above 100 000 000°C.

Other problems

There are many other problems which need more research. For example:

- What materials should the reactor torus be made of? Can they stand being continually bombarded by neutrons?
- How can the fuel be put in, and the used fuel be removed?
- Can superconductors be used to make the coils which produce the magnetic field? (Superconductors have no resistance at low temperatures and so they waste less energy.)
- How can the energy released be transferred to raise steam?
- How can the whole system be made sufficiently reliable, safe and economic to run?

You will shortly be taking part in a group discussion on nuclear fusion. You are the only expert on the world energy scene.

After you have read this, the Chairperson of your group will be asking the kinds of questions a 'man or woman in the street' might ask. Try to answer them as simply as possible, in your own words. Draw diagrams if it helps your answers.

Expert's Briefing 3

World Energy Scene and European Collaboration

The World Energy Scene

Throughout the world we are using up reserves of petroleum, natural gas, coal and uranium. These reserves are limited. We must therefore turn to other energy resources.

Alternative power sources such as geothermal energy, wind and the tides, seem most unlikely to provide all the energy we need.

Coal reserves are large but coal is a useful source of chemicals. Coal can be the base for making a wide range of chemical products. Many people think that coal is 'too good to burn'.

Three sources need to be considered to meet our long-term energy needs:

- Fission breeder reactors
- Controlled nuclear fusion
- Solar energy

The graph in Figure 1 (on the next page) shows one future possibility. Remember it is impossible to predict the future — it is only a guess!

You can see from Figure 1 that coal will be important in the future. Uranium fission in ordinary nuclear power stations will only be useful for a relatively short time.

Fission breeder reactors, like the one at Dounreay in Scotland, could be important. These reactors use plutonium as their fuel. As well as producing energy these reactors can be used to turn uranium into plutonium. They can 'breed' more fuel.

However, there are worries about the dangerous radioactive waste from breeder reactors. Politicians may decide not to build them.

Fusion is a possible solution, but we do not yet know if we can make it work.

Working together on fusion research

There are four main fusion-research programmes being carried out in the world. America, Japan, the USSR and Europe have international agreements to keep each other informed of technical progress.

Fusion research is carried out in many countries in Europe as part of a coordinated programme. The JET (Joint European Torus) project was set up in 1978 as a major research project into nuclear fusion.

The European fusion programme has three long-term objectives.

1 *Scientific*
To show that energy can be gained from controlled nuclear fusion.

2 *Technical*
To prove that it is possible to design and construct a machine that will produce electricity from fusion.

3 *Commercial*
To show that a fusion powered nuclear station could produce electricity economically on an industrial scale.

The JET project will study the first of these. The costs are immense. European collaboration is needed to share the costs.

The cost of the JET project up to 1992 is estimated as £750 million. This covers design, construction and operation.

80 per cent of the cost is paid by Euratom (European Atomic Energy Community). 10 per cent is paid by the UK where the experiment is based.

The remainder is paid by the countries taking part in the experiment.

Key to the terms in Figure 1.

Energy sources:
NG Natural Gas
FUS Nuclear fusion
NUC Nuclear fission
REN Renewable sources (wind, solar)
HYD Hydroelectric power
N-C Renewable sources which are not commercial (firewood and dung)

In this graph all the energy sources are compared to oil. Gtoe stands for Gigatonnes of oil equivalent.

(1 gigatonne = 1 000 000 000 tonnes)

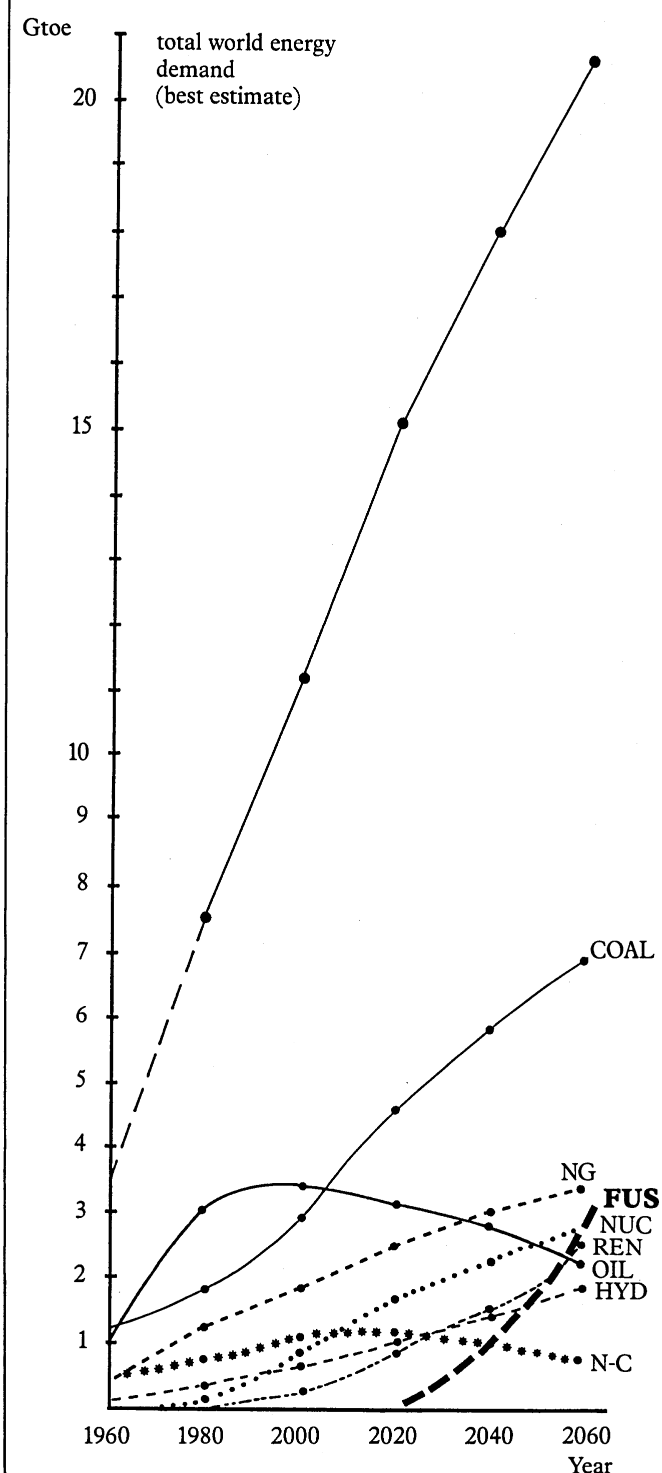


Figure 1 Possible use of energy sources up to the year 2060

Expert's Briefing 4

The advantages and disadvantages

You will shortly be taking part in a group discussion on nuclear fusion. You are the only person in your group who has read this briefing, so you will be the expert on the advantages and disadvantages.

After you have read this the Chairperson of your group will be asking the kinds of questions a 'man or woman in the street' might ask. Try to answer them as simply as possible in your own words. Draw diagrams if it helps.

Advantages of fusion power

1 New sources of energy will be required as oil becomes increasingly scarce and coal is needed as a raw material for industry. Fusion could become that major new source of energy.

2 Fusion fuels are very plentiful, cheap and are well distributed throughout the world. The first generation of fusion power stations will use deuterium (from water) and lithium (mined from the earth). Eventually it is hoped that the more difficult fusion reactions using deuterium alone will be used. This would provide an almost limitless source of energy.

3 Small quantities of fuel are required. Only about one tonne of fuel per year would be used in a 1000 megawatt fusion power station.

4 The fusion reactor will be a very safe system. At any given time the amount of fuel in the reactor will only be sufficient for a few tens of seconds' operation.

5 Fission reactors produce long-lived radioactive products, which require storage and supervision for very long periods of time. Fusion reactors do not produce these dangerous products. There will be no radioactive waste fuel from a fusion reactor.

6 Conventional power stations release chemical pollutants into the atmosphere, causing acid rain and other problems. Fusion reactors do not.

Disadvantages

1 It has not yet been proven that fusion can be made to work on an industrial scale.

2 A fusion reactor is likely to be very expensive to build, although the fuel costs will be very low.

3 The structure of the reactor will become radioactive and the reactor vessel (torus) will need to be replaced several times during the life of the reactor. However the radioactivity can be cut down by choosing materials carefully. Storage of radioactive waste may be needed for less than 100 years.

4 Fusion power is only suitable for highly industrialised nations. It is not likely to be appropriate for developing countries.

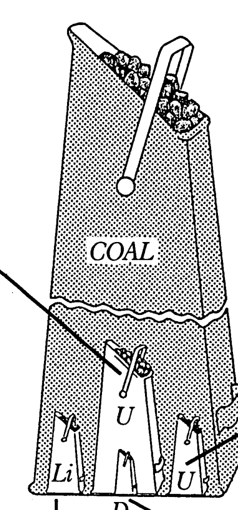
Do you know that . . .

To provide the equivalent of the *world's annual electricity consumption,* in power stations, we would have to use each year:

1 700 000 000 tonnes of coal

or
85 000 tonnes of uranium in ordinary fission reactors

or
1 000 tonnes of uranium in fast-breeder fission reactors



or
1 000 tonnes of lithium in a deuterium-tritium fusion reactor

or
135 tonnes of fuel in a deuterium-deuterium fusion reactor

Figure 1

Chairperson's Briefing

You are Chairperson of a group of students. It is your job to ask questions and chair a discussion on nuclear fusion power. Much of the success of the session depends on how well you do your job!

Everyone in your group will have read the General Briefing on nuclear fusion. Each member (except for you) will also have read one Expert's Briefing. The Expert's Briefings give details about:

1 The containment problem
How can the very hot plasma be kept in place?

2 Getting the conditions right
How can the conditions for fusion be achieved?

3 The world energy scene
What will be the demand for electricity in the future ? How can the demand be met?

4 Advantages and disadvantages of fusion power
Is fusion power likely to be safe? Will it be economical if it can be made to work? Will it create pollution problems?

You will begin by asking some specific questions about nuclear fusion power. You need not stick to the suggested questions if there are others you want to ask. These questions will probably be answered by one of the Experts, though you should allow others to answer if they wish. *Try to act as a 'man or woman in the street' who is trying to find out about nuclear fusion.*

Encourage the Experts to answer in their own words - do not let them read out from the Briefing sheets! Let the Experts draw diagrams on paper, on a blackboard or on an overhead projector if they wish.

After the specific questions, you will raise some general points for discussion. By this time your group should have a reasonable idea of the facts behind nuclear fusion power. Try to encourage everyone to enter into the discussion.

You will find the suggested questions on sheet CB2.

Specific questions

1 *Why do the experts think that we will need an energy source like fusion in the future?*

2 *What are the fuels for fusion?*

3 *What is a Tokamak?*

4 *What is a plasma?*

5 *What temperature must be reached before fusion can start?*

6 *How is the temperature raised to the required temperature?*

7 *Why is it difficult the achieve the conditions needed for fusion?*

8 *What are the main advantages of fusion power?*

9 *How can energy from fusion be used to generate electricity?*

10 *Where is fusion research being carried out?*

11 *Why is fusion research being organised by a group of countries working together?*

General points for discussion

Encourage everyone to take part. Some of these may have already been covered in the 'Specific questions' session, in which case you could leave them out.

- Do we really need nuclear fusion - if so why?
- Do the possible benefits justify the enormous effort required?
- Will fusion give cheap, clean, inexhaustible energy?
- Will fusion power be safe ?
- Is it right to share our knowledge of fusion with other countries?
- Will fusion power solve the energy needs of developing countries if it can be made to work?
- Could we speed up research to get fusion power more quickly? If so how?
- Would it be better to spend the money on research into alternative energy sources instead of fusion research?
- Instead of spending all this money and effort on fusion research, wouldn't we do better to try and cut down the amount of energy we use?