OCR
RECOGNISING ACHIEVEMENT

ADVANCED SUBSIDIARY GCE **2852/01**

CHEMISTRY (SALTERS)

Skills for Chemistry: Open-Book Paper

For issue on or after

14 FEBRUARY 2008

Your report must be handed in by the deadline given by your teacher. You will be given two weeks to complete your report.

CUP/T46192

This paper consists of two articles about radioactive decay, nuclear fission and nuclear fusion.

1 Using between 800 and 1000 words, write a report in which you do the following:

- **Discuss, with the use of examples, the main differences between α- and β-decay and explain how nuclear fission reactions differ from natural radioactive decay. [6]**
- **Explain the role of hydrogen nuclei and helium nuclei in the synthesis of elements in stars. Give a detailed explanation of the nuclear changes that happen when lithium forms in stars. [5]**
- **Describe, with the use of examples, the main characteristics of fission and fusion reactions. Explain how each type of reaction produces energy and describe how these reactions are controlled. Outline the main advantages and disadvantages of using fission and fusion processes for generating electricity. [12]**
- **Outline the main challenges that scientists face in developing fusion power stations. [3]**

2 When you have finished writing your report, summarise the main **CHEMICAL** points of your report using up to 50 words on the Summary Sheet provided.

Before you start, read carefully the 'Notes for Guidance' on the next page.

This document consists of **12** printed pages and an Insert.

Notes for guidance

1 Your report should be of between 800 and 1000 words. An excess of 1000 words will indicate poor structure and unselective choice of material, so that full credit will not be available. You should indicate the number of words on each page in the margin at the foot of the page.

2 **Your report should demonstrate an understanding of the chemical issues involved. It should be aimed at an audience with an understanding of chemistry to Advanced Subsidiary GCE level. It should have a clear and helpful structure and should show evidence of planning.**

3 To help you understand the articles in this paper, you are encouraged to use books and other written sources of information, but **your report should be based closely on the information given in the question paper**.

4 Your report should be illustrated by pictures, diagrams, tables, flow charts, graphs, etc., as appropriate. Remember that these can often be used to replace words in the text. Illustrations should be relevant, concisely labelled and positioned appropriately with links to the text. The inclusion of large blocks of text in such illustrations is discouraged; any such text will be included in the word count (otherwise text in illustrations is excluded from the word count).

5 **You should take care to use technical and scientific terms correctly and to write in clear and correct English.**

6 You may hand-write or word-process your report. Remember that if subscripts, superscripts, arrows in equations, etc. are not available on your word-processor, these must be drawn in correctly and clearly by hand.

7 At the end of your report, you should list clearly any sources you have used. Your list should contain at least **two relevant sources** as well as the articles supplied. (At least one of these should be from outside the Salters Advanced Chemistry course materials.) The list of references is not included in the word count.

8 You should refer to these references in your report where appropriate. Where you have incorporated material into your report which is copied directly from the articles in the question paper or from elsewhere, the **text must be annotated** and the source properly acknowledged. However, extensive copying from the articles or from other sources will not gain credit.

9 Your report should be written on unheaded A4 paper with a hole in the top left hand corner. Pages should be numbered and should have a **clear margin on the right hand** side. You should **write on one side of the paper only** and each separate sheet should be marked with your name or candidate number.

10 **Your summary should be written on the special sheet provided.**

11 When you have finished, tie the sheets together **loosely** or use a treasury tag, so that they turn over freely, with your Summary Sheet on the top. Do not use staples or paper clips and do not put your report in a plastic folder.

Article 1

Lise Meitner

Radiochemist, physicist and co-discoverer of nuclear fission

adapted from 'Lise Meitner Radiochemist, physicist and co-discoverer of nuclear fission' by Gordon Woods, Chemistry Review, Volume 16, Number 1, September 2006.

There were very few women in science until the middle of the twentieth century. This was mainly a result of the intolerant attitude of the scientific establishment, which discouraged women from engaging in academic study. Only those women who showed great determination were able to succeed in the male-dominated scientific community. Lise Meitner was a radiochemist and physicist who had to struggle against dual prejudices. Not only did she have to prove herself to her male colleagues, but she also faced the problem of being a Jew in Nazi-occupied Europe.

Lise Meitner (1878–1968)

Meitner studied physics in Vienna under Ludwig Boltzmann. She completed her doctorate in 1905 (she was the second woman to gain a doctorate in science in Vienna) before moving to Berlin to the newly created Kaiser Wilhelm Institute. There she worked as a lecturer and carried out research into radioactivity, a subject that crosses the boundaries between chemistry and physics. Incredibly, women were not allowed access to the main laboratory, so instead Meitner had to work in the former carpenter's shop for the first two years, until the regulations changed.

Meitner's original work focused on **β-decay** from radioactive elements, while Otto Hahn (at the same institute) was involved with more chemical aspects of these elements. Chemists had long believed that elements were unchangeable, and yet it was observed that through **α**- and **β-decay** atoms could change from one element into another (see Box 1). This was a phenomenon worthy of study.

Interrupted by War

In 1912, Hahn and Meitner began working together at Berlin-Dahlem. They collaborated in a search for the element that could be regarded as the 'parent' of the radioelement actinium, which had been discovered in small concentrations in some uranium minerals in 1889. But the start of the First World War interrupted their work: Hahn had to join the German army and Meitner became a radiologist at a military hospital for the Austrian army. Nevertheless, they managed to do some

Box 1 Radioactive decay

During radioactive decay, atoms of one element are changed into atoms of another element through the emission of α- or β-particles from their unstable nuclei. With **α-decay** an atomic nucleus disintegrates and emits an α-particle, which contains two protons and two neutrons – equivalent to a helium-4 nucleus.

$$^{224}_{88}\text{Ra} \rightarrow {}^{220}_{86}\text{Rn} + {}^{4}_{2}\text{He}$$

In **β-decay**, a neutron in the nucleus of an atom is converted into a proton and an electron. The electron is released as a β-particle.

$$^{225}_{88}\text{Ra} \rightarrow {}^{225}_{89}\text{Ac} + {}^{0}_{-1}\text{e}^{-}$$

research when they were on leave, helped by the fact that some radiochemistry experiments need long gaps between measurements. In March 1918, they identified proto-actinium (now called protactinium) with atomic number 91 and symbol Pa. This element decays to actinium by α-decay:

$$^{231}_{91}\text{Pa} \rightarrow {}^{227}_{89}\text{Ac} + {}^{4}_{2}\text{He}$$

Meitner was highly regarded in the male-dominated world of physics and in 1918 she was appointed Head of Radiation Physics at the Kaiser Wilhelm Institute. Hahn and Meitner resumed their personal collaboration in 1934 in investigating some results obtained by the Italian nuclear physicist Enrico Fermi (after whom element 100, fermium, is named). Fermi's experiments involved bombarding atoms of heavy elements with low energy neutrons. (Neutrons had been discovered only two years earlier.) Neutrons are uncharged and so are not deflected by the electrically charged electrons outside nor by protons inside nuclei. This makes them good ammunition for hitting the atomic nucleus in the hope that they fuse with it and make the nucleus heavier. Fermi hoped to make new elements, heavier than uranium, but his results were confusing and difficult to explain.

Meanwhile, the rise of Nazism in Germany put Meitner in danger due to her Jewish origins. She fled, with the help of scientist friends, to Stockholm, where, at the age of 60, she learned to speak Swedish and set up a new research group!

Family collaboration

Back in Germany, Hahn continued to work on bombarding nuclei with neutrons. He bombarded uranium atoms with low energy neutrons and, like Fermi, he was puzzled by the products. Instead of getting heavier nuclei, as he had expected, he obtained small amounts of atoms that were chemically similar to the lighter atoms thorium and radium. Once again, radioactivity was difficult to understand.

Hahn wrote to Meitner to tell her about his results. She discussed the problem with her nephew, Otto Frisch, another physicist, when they were together at Christmas in 1938. As they talked, they made a huge mental leap to explain the puzzling results. Later Frisch said, '*The idea took shape that this was no chipping or cracking of the nucleus, but rather a process to be explained by Bohr's idea that the nucleus was like a liquid drop; such a drop might elongate and divide itself*.'

Frisch and Meitner managed to prove this idea by calculation, showing that the 'radium' that Hahn thought he had made was actually barium (barium and radium are similar because they are both in Group 2). The uranium nucleus had been broken into two roughly equal parts (differing in mass number by between 30 and 70) – the atom had been split. Frisch and Meitner published a joint paper about their novel ideas, coining the term **nuclear fission** to describe the process of splitting an atom. **Fission reactions** differ from **radioactive decay** both in the way that the reaction must be started and in the type of products that are formed.

Fig. 1 shows the proportions of fission products for uranium-235.

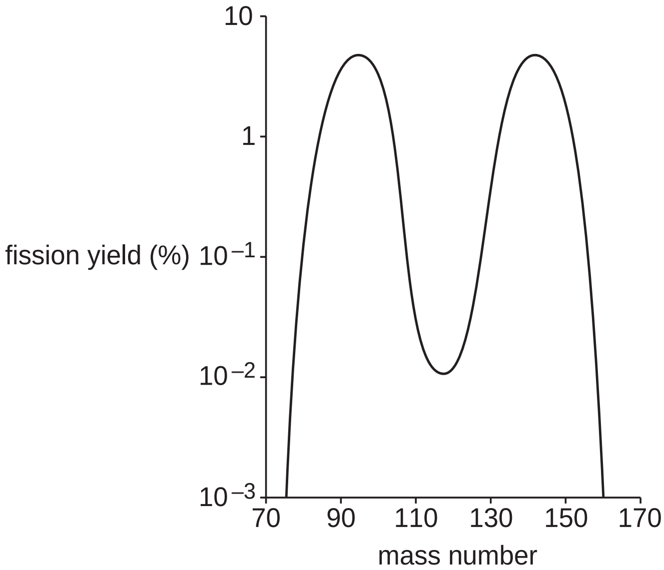


Fig. 1 Distribution of the possible fission fragments from ^{235}U

Nuclear fission

Nuclear fission of ^{235}U can also produce two or three more neutrons and release a large quantity of energy. The energy is produced from the direct conversion of some of the nuclear mass into energy, according to the famous Einstein equation:

$$E = mc^2$$

where E is the energy, m is the mass and c is the velocity of light.

The process of nuclear fission can be thought of like the oscillation of a drop of liquid – if the vibrations are violent enough the droplet splits in two (see Fig. 2). If an atom of ^{235}U is given sufficient energy through the absorption of **one**

neutron, it enters an excited state and begins to oscillate. When the oscillations become unstable, the nucleus splits into two similar nuclei of medium mass, **emitting more neutrons** in the process. These neutrons can cause further fission in other nuclei, thus producing a chain reaction.

One possible fission reaction of uranium-235 is:

$$^{1}_{0}n + {}^{235}_{92}U \rightarrow {}^{89}_{36}Kr + {}^{144}_{56}Ba + 3\,^{1}_{0}n$$

The huge amount of energy that fission reactions release can be used peacefully to provide electricity (see Box 2), or in war as an atomic bomb. During the Second World War, the USA and Germany each sought to make atomic weapons, but Meitner, safe in Sweden with dual Swedish and Austrian nationality, was able to avoid this line of research. She hoped, in vain, that making a nuclear bomb would be impossible.

In 1944, Hahn was awarded the Nobel chemistry prize for his work on nuclear fission, but Meitner was overlooked, although many people felt that the prize should have been shared. They both died in the same year, 1968. Element 109 was named meitnerium (Mt) after her, and element 108 was originally called hahnium after Hahn, but was later renamed to hassium (Hs) after the German nuclear research centre in Hesse. There are far fewer elements named after scientists than there are Nobel prize winners, so perhaps in this way, Meitner got the recognition she deserved.

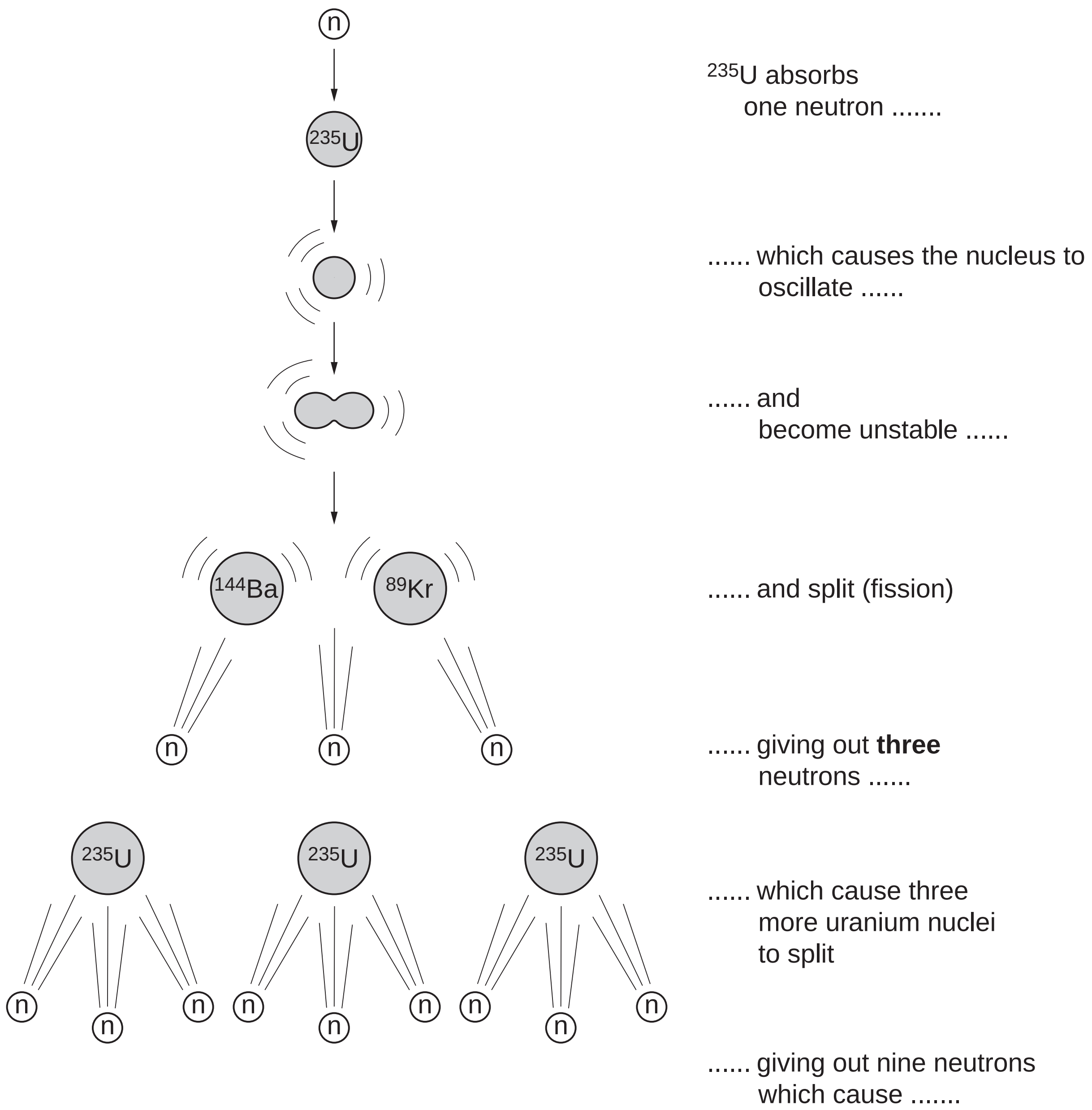
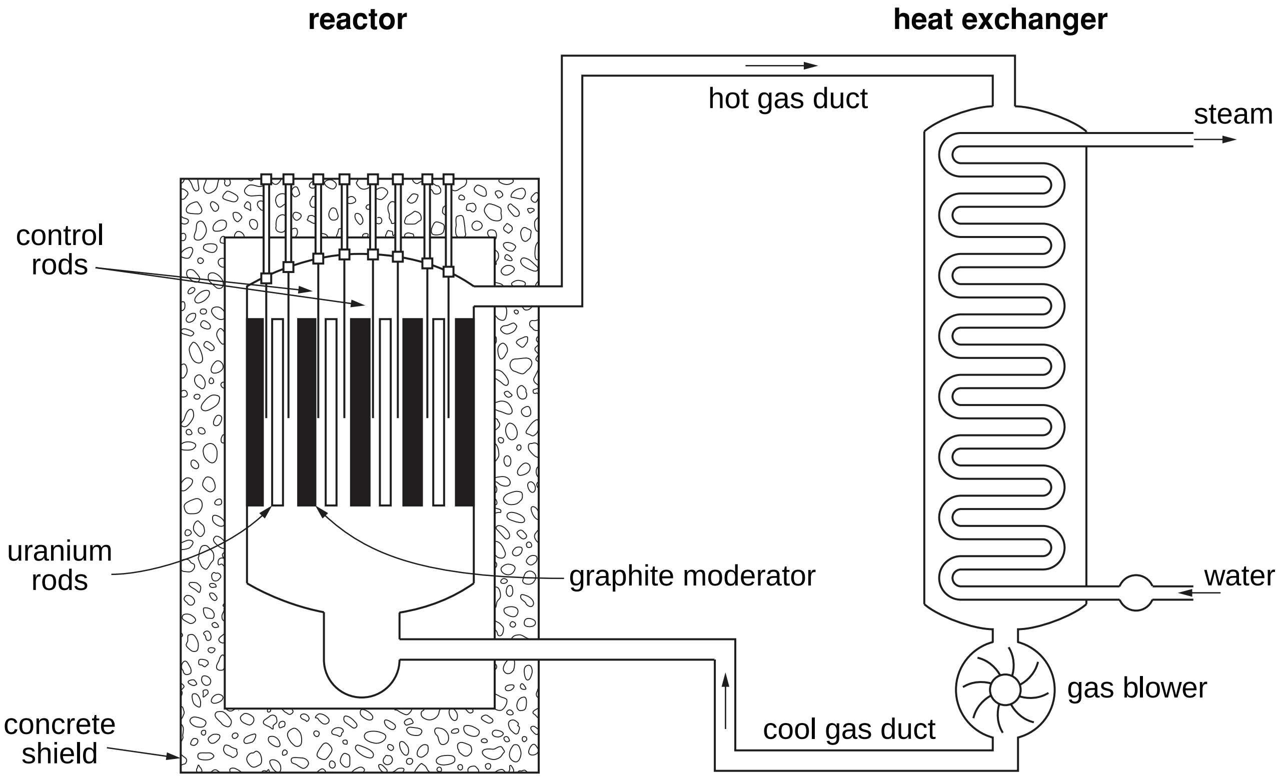


Fig. 2 Schematic illustration of nuclear fission

Box 2 Using nuclear fission to generate electricity

The fission process is started by slow moving neutrons hitting the nucleus of a ^{235}U atom. Each nucleus that splits produces three neutrons, creating a chain reaction which, if unchecked, causes the process to accelerate and become uncontrollable. This is similar to the process that was used to develop the first nuclear bombs. To generate electricity, nuclear fission reactions are controlled in a nuclear reactor. The first nuclear reactors used natural uranium which contains a mixture of two isotopes of uranium, ^{238}U and ^{235}U.

^{238}U does not undergo fission in the reactor, so when neutrons collide with this isotope, they are harmlessly absorbed and the chain reaction is interrupted. The reactor has another two mechanisms for controlling the reaction: the **graphite moderator** and the **control rods**, which are made from boron coated steel. The neutrons that are produced when a nucleus splits are very fast moving. The moderator slows them down enough so that they cause fission reactions when they collide with ^{235}U nuclei. The **control rods** absorb neutrons. The control rods can be moved in and out of the reactor to control the rate of fission reactions. If they are pushed all the way in, they absorb all the neutrons, the reaction stops and the reactor shuts down. Moving them partly in and out enables the operators to control the rate at which the fission reactions occur.



As well as the fission of ^{235}U in the reactor, some secondary reactions occur. For example,

- ^{238}U forms ^{239}U when it is bombarded with a neutron
- ^{239}U undergoes β-decay to form ^{239}Np (neptunium)
- ^{239}Np undergoes further β-decay to form ^{239}Pu (plutonium).

The fission reactions in the reactor generate a great deal of energy. The reactors are cooled by passing either a liquid (usually molten sodium metal) or a gas (carbon dioxide) through pipes that go through the reactor. The heat is then used to boil water to form steam which then turns turbines to produce electricity.

cont.

Box 2 cont.

More modern nuclear reactors, such as 'fast breeder' reactors, use other elements such as plutonium as fuel. The main drawback to the use of nuclear power is the fact that the waste produced remains very harmful for several thousand years. Hence the disposal and storage of nuclear waste poses major problems.

[Turn over

Article 2

Fusion
Powering the future?

adapted from 'Fusion, Powering the Future?' by Chris Warrick, Chemistry Review, Volume 16, Number 1, September 2006 and 'Lithium' by Chris Ennis, Volume 15, Number 31, February 2006

Harnessing fusion – the energy source of the Sun – has long been a dream of science and could provide an almost limitless supply of energy in an environmentally responsible way. With the construction of a new reactor-scale fusion device – ITER – about to start in Cadarache in the south of France, maybe the dream is about to become a reality. You may think that only physicists work on nuclear fusion, but chemical processes also play an important role in addressing some of the fundamental challenges that face nuclear-fusion research, several of which are highlighted in this article.

You may be wondering why a new form of energy production is needed. Worldwide energy use is expected to double in the next 40 years. Lifting developing countries out of poverty will require even more energy. At present, 80% of the world's energy is generated by burning fossil fuels – driving global climate change and generating pollution. The global response to these issues should be a cocktail of solutions, including energy efficiency, more renewable and nuclear-fission energy sources (as used in our current nuclear power stations) and more research into new technologies such as fusion.

Fusion power is an attractive option for several reasons:

- The fuels (isotopes of hydrogen) are abundant, offering a genuinely long-term source of power.
- The radioactivity of the structure of a fusion power station is short lived (50–100 years) compared with that of nuclear fission, in which highly radioactive waste (actinides) is produced. Some of the fission by-products can take several thousand years to decay fully.
- High safety – the fusion reaction cannot get out of control because only small amounts of fuel are used.

Nothing new under the Sun

The idea of extracting the net energy from controlled fusion reactions is nothing new. The difficulty is recreating on Earth the reactions observed in the Sun. Fusion reactions in the Sun produce elements by nucleogenesis (see Box 1).

If fusion reactions could be controlled on Earth, the energy given out could potentially be used to generate electricity. The problem for scientists is to reproduce fusion reactions under conditions that can be safely managed. The JET project (Joint European Torus) is the focus of research efforts in Europe. Unlike fission (splitting apart) of heavy nuclei, the fusion of light nuclei requires sustained high temperatures. At normal temperatures on Earth, the repulsion between the two nuclei would be too great for them to fuse together. At higher temperatures, the nuclei are moving much more quickly and collide with so much energy that this repulsive energy barrier can be overcome. Once the nuclei are close enough, the strong nuclear forces which hold protons and neutrons together in the nucleus take over and the nuclei fuse.

The chosen reaction in experiments on Earth is the fusion of deuterium (available from water) and tritium – two heavy isotopes of hydrogen. Under the right conditions, these nuclei fuse to produce helium and a neutron along with excess energy (see Box 2). For this reaction to occur the particles need to form a high-density, super hot (around 150 million °C!), ionised gas – a **plasma**. When the temperature is high enough, the electrons escape from the nuclei, producing a plasma of positive ions in a sea of delocalised electrons. Such conditions are very difficult to create on Earth but gases in stars like our Sun exist naturally as a plasma.

The plasma must be kept away from the vessel walls using a confinement method, which minimises heat losses from the system. This confinement keeps the energy inside the plasma long enough for the fusion reaction to become established, so that more power is released than is needed to keep the fuel hot.

To keep the plasma away from the walls of the vessel, a **tokamak** is used (the name comes from

Box 1 Nucleogenesis

Have you ever wondered where the chemical elements come from? Hydrogen and helium are by far the most abundant elements, accounting for approximately 89% and 11% of the atoms in the universe, respectively. Heavier chemical elements such as lithium are made from these simple elements in a variety of processes collectively called **nucleogenesis**.

Most nucleogenesis occurs in stars. There are many different kinds of stars, reflecting the different processes that occur within the stars themselves. In the Sun, the closest star to Earth, hydrogen is converted to helium in nuclear fusion reactions:

$$4\,^{1}H \rightarrow \,^{4}He + \text{subatomic particles}$$

This reaction liberates vast quantities of energy (around $2.5 \times 10^{9}\,kJ\,mol^{-1}$, roughly six million times the average molar bond enthalpy of a carbon–hydrogen bond and roughly three million times the molar enthalpy change of combustion of methane). This energy reaches Earth as heat and light.

As stars like the Sun evolve, they use up most of their hydrogen and begin a new series of fusion reactions, in which helium nuclei react to form beryllium, carbon, oxygen, neon and magnesium:

$$2\,^{4}He \rightarrow \,^{8}Be$$

$$^{4}He + \,^{8}Be \rightarrow \,^{12}C$$

$$^{12}C + \,^{4}He \rightarrow \,^{16}O$$

$$^{16}O + \,^{4}He \rightarrow \,^{20}Ne$$

$$^{20}Ne + \,^{4}He \rightarrow \,^{24}Mg$$

At each stage of these processes, energy is given out.

Once the helium has been used up, the star begins a new series of processes using carbon nuclei to produce a wide range of elements. Initially, carbon nuclei combine:

$$^{12}C + \,^{12}C \rightarrow \,^{24}Mg$$

$$^{12}C + \,^{12}C \rightarrow \,^{23}Na + \,^{1}H$$

$$^{12}C + \,^{12}C \rightarrow \,^{20}Ne + \,^{4}He$$

The production of small amounts of hydrogen and helium nuclei makes it possible for the star to synthesise most of the elements in the first three periods of the Periodic Table. Two routes for the generation of lithium are:

Route 1 $\quad ^{4}He + \,^{3}H \rightarrow \,^{7}Li$

Route 2 $\quad ^{4}He + \,^{3}He \rightarrow \,^{7}Be$

$^{7}Be + \text{electron} \rightarrow \,^{7}Li$

Route 2 is interesting, because the collision between an atom and an electron is causing changes to the *nucleus* of the atom. In this case, the proton number and the structure of the nucleus is changed when the electron reacts with it.

After the Universe cooled, lithium could be produced by the action of energetic cosmic rays on elements such as carbon, nitrogen and oxygen. A small amount of lithium can be synthesised in super novae (exploding stars), in which heavier elements can also be created.

Box 2 Fusion reactions

Under the right conditions, deuterium and tritium atom fuse to form a helium atom and a neutron.

$$^{2}_{1}H + ^{3}_{1}H \rightarrow ^{4}_{2}He + ^{1}_{0}n$$

Excess energy is released from the fusion reaction because of the lower binding energy of the helium nuclei compared to those in deuterium and tritium. The combined mass of the products (4.974 proton masses) is less than the mass of the reactants (4.993 proton masses) – the 'lost' mass is converted to energy, according to Einstein's equation:

$$E = mc^2$$

where E is the energy, m is the mass and c is the velocity of light.

'toroidal magnetic chamber' in Russian!). This device contains the hot plasma in a doughnut shape within a vacuum vessel. The plasma is made of charged particles (ions and electrons) which are kept away from the walls by powerful magnetic fields that are generated by large coils that run around the vessel. The plasma is heated by the powerful electric currents that are induced in it as well as by microwaves that are directed into it and beams of fast neutron particles. The largest tokamak in the world is run by the JET project at Culham Science Centre in the UK.

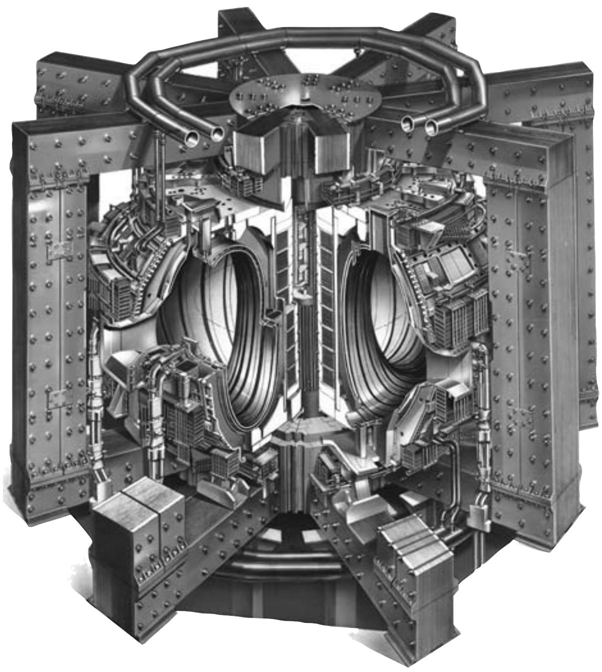


Fig. 1 The JET tokamak

Too hot to handle

The walls of a tokamak are usually made out of carbon fibre composite tiles. Carbon is chosen because it is not damaged by the very high temperature of the plasma. Although the plasma

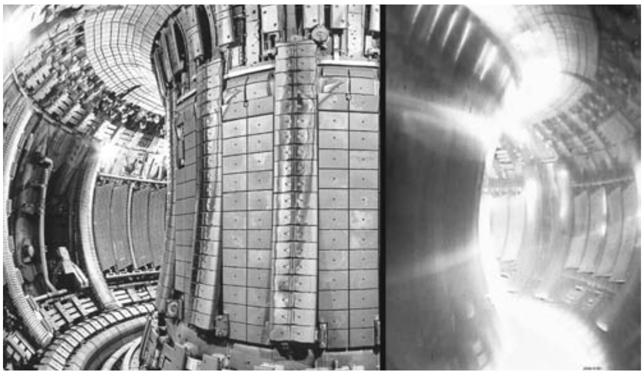


Fig. 2 Interior (left) and plasma inside (right) the JET vessel

does not touch the main walls of the vessel, it does touch the walls at the bottom. This is necessary so that the excess helium ions that are produced during the fusion process can be pumped away.

Where the plasma touches the walls, the carbon tiles are eroded by deuterium or tritium ions and neutral species, producing hydrocarbons. Methane, CH_4, is the main product of this erosion but hydrocarbons with two or three carbon atoms are also formed. Further reactions occur as these hydrocarbons are bombarded with protons, resulting in the formation of reactive radicals. These combine with each other on the vessel surfaces to form hydrocarbon films (Fig. 4).

These films cause problems because they trap the tritium and deuterium fuel ions in the walls of the device so that they are not circulating in the reacting plasma to produce any energy. Also, if the film gets thicker, it begins to flake off (Fig. 4), resulting in dust particles which can be absorbed into the plasma, affecting its purity and performance. Ways to reduce the growth of hydrocarbon films are being studied.

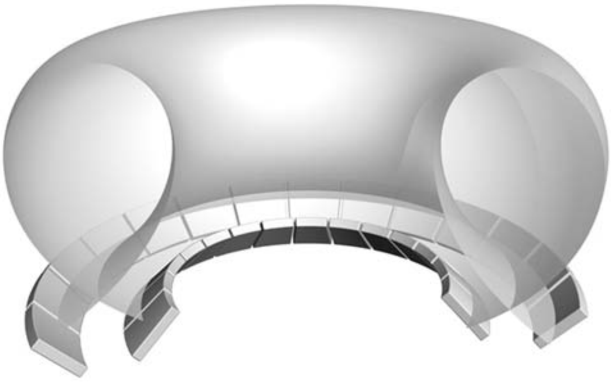


Fig. 3 The divertor region inside a tokamak. Field lines are crossed to form a closed plasma region in contact with the divertor tiles at the bottom

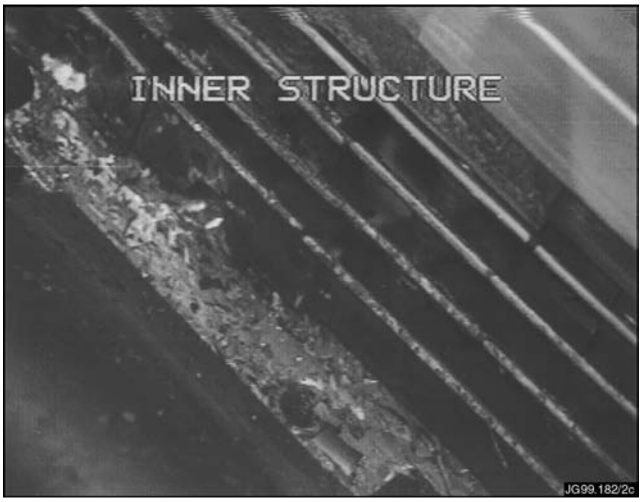


Fig. 4 Photograph of flakes and dust resulting from the break-up of hydrocarbon films deposited on cool surfaces in the tokamak

An international effort

Despite these problems, scientists are confident that a fusion power station can be built based on a tokamak design. The International Tokamak Experimental Researcher (ITER, Fig. 5) is being built at Cadarache in the south of France and should be ready for operation in 2015. It should produce 500 MW of fusion power – at least ten times the power needed to heat the plasma. It will be used for testing the system on a power station scale as well as for testing new types of wall tiles made from beryllium. The full scale prototype will also be used to check that the structure and materials can withstand years of neutron flows produced from the fusion reactions. Scientists hope that the technology will be ready to produce electricity commercially in around 30 years time.

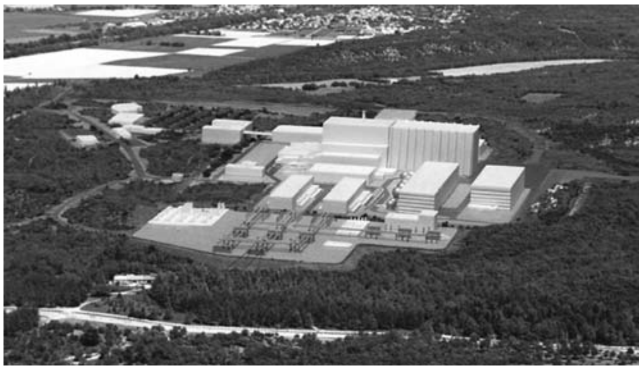


Fig. 5 Model of the ITER being built at Cadarache, expected to be operational in 2015

END OF QUESTION PAPER

Copyright Acknowledgements:

Article 1 text and Fig. 1	Adapted from G. Woods, *Lise Meitner: Radiochemist, physicist and co-discoverer of nuclear fission*, Chemistry Review, September 2006. Reproduced by kind permission of Philip Allan Updates.
Article 1 photo	© Emilio Segre Visual Archives / American Institute of Physics / Science Photo Library
Article 1, Box 2 drawing	Adapted from *Chemistry Today*, © E. Henderson, Macmillan Publishers Ltd, 1977. Reproduced by kind permission of Macmillan Publishers Ltd.
Article 2 text	Adapted from C. Warrick, *Fusion: Powering the Future?*, Chemistry Review, September 2006. Reproduced by kind permission of Philip Allan Updates.
Article 2 Figs. 1, 2, 3 and 4	© EFDA-JET, www.jet.efda.org. Reproduced by kind permission of EFDA-JET.
Article 2 Fig. 5	© CEA, www-cadarache.cea.fr. Reproduced by kind permission of CEA.
Article 2, Box 1 text	Adapted from C. Ennis, *Box1: Nucleogenesis* (*p21*), Chemistry Review, February 2006. Reproduced by kind permission of Philip Allan Updates.