**Chapter 31: Fission, Fusion and Nuclear Energy**

***Please remember to photocopy 4 pages onto one sheet by going A3→A4 and using back to back on the photocopier***

*We made the mistake of lumping nuclear energy in with nuclear weapons, as if all things nuclear were evil. I think that’s as big a mistake as if you lumped nuclear medicine in with nuclear weapons.*

Patrick Moore,
former Director of Greenpeace International

**Why is nuclear fusion not used at present to generate electricity for commercial use?**

**Nuclear Fission**

**Nuclear fission** is the break-up of a large nucleus into two smaller nuclei with the release of energy and neutrons\*.

Natural uranium is made up of two isotopes: 235U (0.7%), and 238U (99.3%). Only U-235 undergoes fission.

This occurs if it is bombarded with fast-moving or slow-moving neutrons, but is more likely to occur if the neutrons are *relatively* slow moving.



This reaction is represented as follows:

**235U + 1 neutron  92Kr + 141Ba + 3 neutrons + K.E. \***

The neutrons produced are fast moving and *may* trigger further fission.

**E = mc2**

The total mass on the left-hand side is greater than the total mass on the right-hand side. The mass which has disappeared has been converted (re-manifested) into the kinetic energy of the particles on the right (see note below).

**Chain Reactions**

If the mass of the sample is above a certain critical mass, the process will become self-sustaining (as a result of the new neutrons colliding into more uranium atoms) and a chain reaction will occur.

A chain reaction is a self-sustaining reaction where fission neutrons go on to produce further fission (giving more neutrons) etc.

If the mass is below the critical mass the reaction will simply fizzle out**\*.**

**This process also occurs in a nuclear reactor, but at a controlled rate\*.**

*The energy produced by the atom is a very poor kind of thing. Anyone who expects a source of power from the transmutation of these atoms is talking moonshine”*

Rutherford, 1933

*Do not worry about your difficulties in mathematics; I can assure you that mine are still greater.*

Albert Einstein to a junior high school student Barbara Wilson, January 7, 1943.

*The mathematical education of the young physicist [Albert Einstein] was not very solid, which I am in a good position to evaluate since he obtained it from me in Zurich some time ago.*
Hermann Minkowski

**Nuclear Reactors**



* The fuel is *natural* *uranium*.
* The moderator is *graphite* or *heavy-water*

This slows down the fast moving neutrons to enable further fission in 235U rather that being absorbed in 238U.

* The control rods absorb neutrons; they look like sleeves.

Lowering them over the fuel rods prevents the neutrons from one fuel rod reaching the next rod, and so they control the rate of the reaction. Lowering them completely causes the reaction to stop.

* A heat exchanger is a device that allows heat from the hot radioactive coolant to pass to another series of pipes containing water without having to mix together. This turns the water into steam which then goes on to power a turbine.

**Environmental impact of fission reactors**

Positive: No CO2 emissions, no greenhouse gases. Negative: Radioactive waste, potential for major accidents.

**Nuclear Fusion\***

**Nuclear Fusion** is the combining of two small nuclei to form one large nucleus with the release of energy.

Example

 *= deuterium (one proton plus one neutron)*

 *= tritium (one proton plus two neutrons)*

 *Both nuclei are hydrogen because it is the number of protons that determines the identity of the element, and both of these have one proton.*

Note that this involves the combination of 2 positively charged particles.

To overcome this Coulombic repulsion (remember Coulomb’s Law?) a large amount of energy must be supplied.

**Why is a fission reactor a more viable source of energy than a fusion reactor?**

1. Easier to initiate reaction
2. Fission can be more easily controlled

**Advantage of Fusion over Fission:**

1. Less radioactive waste.
2. Deuterium is readily available from the oceans.
3. No dangerous chain reactions.

**So why don’t we have fusion reactors producing electricity for us now (instead of fission reactors)?**

There is, as of yet, no way to maintain and control the high temperatures required for fusion reactors. There are a couple of prototypes, e.g. ITER in France, but all are a long way from becoming commercial.

**The energy we get from the sun comes from nuclear fusion reactions in the sun\***

**Leaving Cert Physics Syllabus**

|  |  |  |  |
| --- | --- | --- | --- |
| **Content** | **Depth of Treatment** | **Activities** | **STS** |
|  |  |  |  |
| Nuclear Energy | Principles of fission and fusion. | Interpretation of nuclear reactions | Fusion: source of Sun’s energy.Nuclear weapons. |
|  | Mass as a form of energy.Mass-energy conservation in nuclear reactions. | Appropriate calculations | Mass transformed to other forms of energy in the Sun. |
|  | E = mc2 |  |  |
|  | Nuclear reactor (fuel, moderator, control rods, shielding, and heat exchanger). | Audiovisual resource material | Environmental impact of fission reactors.Development of fusion reactors. |
|  |  |  |  |
|  |  |  | Disposal of nuclear waste. |

***“The energy produced by the breaking down of the atom is a very poor kind of thing. Anyone who expects a source of power from the transformation of these atoms is talking moonshine”***

**Rutherford**

**Extra Credit**

**\*Fission is the breaking up of a large nucleus into two smaller nuclei with the release of energy (and neutrons).**

This is the principle behind the original atomic bomb.

So where did the energy come from?

It came from the fact that the total mass of all the particles *after* the explosion was less than the total mass before, and the missing mass (or ‘mass defect’) manifested itself as kinetic energy of the particles produced.

This requires a little attention – if only to acknowledge how weird it is. It is a direct application of Einstein’s famous equation E = mc2.

What it basically means is that mass can be considered as being *a form of energy*! It also throws up the hoary old chestnut ‘what is energy?’, but in this case what it means is that the more mass that disappears, the greater will be the kinetic energy of the particles that are left.

The atomic bomb dropped in Hiroshima in August 6th, 1945, killing over 140,000 people (called *Little Boy*) contained 64 kg of uranium, of which 0.7 kg underwent [nuclear fission](http://en.wikipedia.org/wiki/Nuclear_fission), and of this mass only 0.6 g was transformed into energy (i.e. disappeared), but as a result the other particles produced flew off at enormous speeds, enabling them to produce maximum destruction, misery and carnage.

Isn’t science wonderful?

However as a result of the damage caused by these atomic bombs, scientists began to question the morality of their work like never before. ‘Pugwash’ (www.pugwash.org) is an organisation set up by scientists to promote peace, and many top scientists are members.

**235U + 1 neutron  92Kr + 141Ba + 3 neutrons + K.E.\***

K.E. means that each of the neutrons produced move off at high velocities.

But to acquire this energy some of the original mass had to ‘disappear’. This ‘missing mass’ can be calculating by finding the total mass before and after the reaction and subtracting one from the other.

The energy associated with this missing mass can then be calculated using E = mc2.

**\*If the mass is below the critical mass the reaction will simply fizzle out**

In the original atomic bombs, two pieces of fissile material of sub-critical mass are suddenly brought together using conventional explosives, creating a critical mass and the condition necessary for an uncontrollable chain reaction.

There is a spot in Africa (Gabon I think) where tens of millions of years ago a chain reaction occurred naturally, resulting in what was possibly the world’s first nuclear explosion!

**\*This process also occurs in a nuclear reactor, but at a controlled rate**

The accident in Chernobyl occurred because while the reactor was overheating and the control rods didn’t function properly. There is still debate as to whether this was due to a faulty design or to human error.

**\*Nuclear Fusion**

At the moment more energy is put in to get the particles to collide than we get out from the fusion process, so there are no nuclear fusion plants.

However it is one of the research areas into which science is putting most of its resources.

It is hoped that the breakeven point will be less than 25 years away.

It turns out that the ratio of the mass of the neutron to that of the proton is approximately 1.001.

It is exactly the ‘right’ ratio to allow for nuclear fusion in stars. If it was any different we would not be here.

Scary.

**\*The energy we get from the sun comes from nuclear fusion reactions in the sun.**

So the mass of the sun is decreasing every day. But don’t worry; it’s not likely to run out any day soon.

**1939: Beneath the bleachers of the football stadium at the University of Chicago, Fermi led a team of physicists who released the world’s first controlled chain reaction.** The physicist in charge at Chicago was Arthur Holly Compton.

**COMPTON:**

We entered the balcony at one end of the room. On the balcony a dozen scientists were watching the instruments and handling the controls. Across the room was a large cubical pile of graphite and uranium blocks in which we hoped the atomic chain reaction would develop. Inserted into openings in this pile of blocks were control and safety rods. After a few preliminary tests, Fermi gave the order to withdraw the control rod another foot. We knew that that was going to be the real test. The geiger counters registering the neutrons from the reactor began to click faster and faster till their sound became a rattle. The reaction grew until there might be danger from the radiation up on the platform where we were standing. "Throw in the safety rods," came Fermi's order. The rattle of the counters fell to a slow series of clicks. For the first time, atomic power had been released. It had been controlled and stopped. Somebody handed Fermi a bottle of Italian wine and a little cheer went up. One of the things that I shall not forget is the expressions on the faces of some of the men. There was Fermi's face—one saw in him no sign of elation. The experiment had worked just as he had expected and that was that. But I remember best of all the face of Crawford Greenewalt. His eyes were shining. He had seen a miracle, and a miracle it was indeed. The dawn of a new age. As we walked back across the campus, he talked of his vision: endless supplies of power to turn the wheels of industry, new research techniques that would enrich the life of man, vast new possibilities yet hidden.

**Nuclear *Fission* and Atomic Bombs**

The guy in charge of the Atomic Bomb research project in Los Alamos, New Mexico during WWII was called Robert Oppenheimer.

When he saw the mushroom cloud from the very first atomic bomb which was set off as a trial, he uttered the words ‘*I have become death – the destroyer of worlds’*.

Oppenheimer himself was later considered a ‘security risk’ by the United States government, in spite of there being little if any evidence against him. It may have been because he wanted to scale down investment in nuclear weapons, while another scientist – Edward Teller – wanted the opposite.

Teller was a shrewd operator and got his way, and is now known as the father of the Hydrogen bomb, which we’ll come back to when we get to nuclear fusion.

**Sellafield reprocessing plant**

Sellafield is not a generating station. It takes in uranium which has already been used as fuel and which no longer contains a high enough percentage of uranium 235. It then ‘enriches’ this by bring the percentage of uranium 235 back up to a level where it can again be used.

**So what’s the deal with Iran?**

Under the Geneva deal, Iran agreed to limit its uranium enrichment to 5% and neutralise its stockpile of 20%-enriched uranium. Uranium can be used to build a weapon if it is enriched to more than 90%. At lower levels, it is used to power nuclear reactors.

**Nuclear *Fusion* and Atomic Bombs**

Now while scientists may not be able to control nuclear fusion in nuclear plants, it doesn’t mean that it doesn’t happen. No Sir.

All modern atomic bombs work on the principle of nuclear fusion.

So how do they get the energy necessary to cause two deuterium nuclei to collide?

Easy – they use a traditional nuclear fission atomic bomb.

Ingenious – no?

This was Edward Teller’s baby and not for nothing is he known as the father of the Hydrogen bomb.

The advantage of the Hydrogen (fusion) bomb over the old Atomic (fission) bomb is that the new version releases much more energy. Which is a nice way of saying that it can kill more people. A lot more people.

Apparently this is a good thing.

**Terminology**

You may have noticed that some of the terms are confusing.

After all, both types of bomb (fission and fusion) are ‘Atomic’ and both are ‘Nuclear’.

I guess the way scientists distinguish one from the other is that a Fusion bomb involves hydrogen, and so is called a ‘Hydrogen bomb’.

The other factor is that nobody bothers with the old atomic (fission) bomb any more.

**Heisenberg and the Atomic Bomb**

In WWII while the Allies were working on the Atomic bomb, the Germans were working on their own version.

The main guy was Werner Heisenberg – famous for ‘*Heisenberg’s Uncertainty Principle’*, which all you chemistry students know off by heart, and who was one of the founders of Quantum Theory.

But he miscalculated what the critical mass would be, and as a result the Germans never did produce an atomic bomb.

A question historians wonder about is whether or not Heisenberg did this deliberately in an attempt to sabotage the project for ethical reasons, or was it merely a blunder.

Could it be that if it wasn’t for this one man we would be studying German textbooks instead of English textbooks today?

There is a wonderful play which deals with these issues called ‘Copenhagen’ – highly recommended – go see it if you ever get the chance. It is about at an intriguing meeting that took place between Heisenberg and that other giant of Quantum Theory – Neils Bohr – in Copenhagen in 1942. Was Heisenberg trying to find out what stage the Allies were at in their Atomic bomb research, or was he trying to get Bohr to agree to a non-Nuclear pact?

Or what other possibilities are there?

**Abortions in Greece, January 1987**

As soon as the Chernobyl accident on 26th of April, 1986 was reported in newspapers and on TV, the actual events (initial deaths at the power plant turned out to be 31: fire-fighters and plant workers) rapidly became magnified in several countries and guesses by reporters were wildly inaccurate. Thus in the United Kingdom the *Daily Mirror* on 30 April headlined ‘Please get me out Mummy’, ‘Terror of trapped Britons’ and ‘2000 are feared dead in Nuclear Horror’. The *Detroit Medical News* of 12 May stated ‘So the Russians have started to self-distruct. That is the good news, the bad news is that they are exporting their fall-out across the globe.’ The *New York Post* was most outlandish with ’15,000 Dead in Mass Grave’. TV was not always much better with an American TV network buying for 20,000 US dollars a video purporting to be Chernobyl burning. Unfortunately for them, the views were recognised by Italians as being those of a fire at a Trieste cement factory. An ABC TV newscaster was reported to have said ‘It is one mistake we will try not to make again.’

The more horrific an accident, the ‘better news’ it is supposed to make, and this will not alter. I even found this attitude when trying to find a publisher for my book *Chernobyl – The Real Story*. I believe that I quite rightly claimed that the contents included ‘dramatic pictures’. However, one publisher rejected this claim because, as he said, ‘there were no pictures of dead bodies with legs and arms missing’.

In the aftermath of this incident at Chernobyl, the panic caused by incorrect and inadequate available information was particularly poignant in Greece. Pregnant mothers, because of the ‘scare’, had otherwise wanted pregnancies terminated. The expected number of live births in Greece in January 1987 was some 9,000 but in practice, there were only some 7,000 live births, a 23% reduction in those expected. This is considered by Greek Physicians to be virtually entirely due to the worry concerning the accident and this is corroborated by the number of live births in February and March 1987 being as expected, since for the births expected in these months, relevant information on radiation effects from Chernobyl was available to the Greek physicians and obstetricians.

References:

R F Mould 1988 *Chernobyl –* *The Real Story* (Oxford: Pergamon Press Ltd)

D Trichopoulos 1988 Victims of Chernobyl in Greece *British Medical Journal* **295** 1100

Extract from a book entitled *Mould's Medical Anecdotes*

**Living with Albert**

Einstein married Mileva Marić in 1903, but by 1914, things had soured (he was actually having an affair with one of his cousins at the time of writing this) and the scientist wrote his wife this letter of rules she had to obey if she wanted to stay married:

You make sure:

1. You make sure that my clothes and laundry are kept in good order and repair.That I receive my three meals regularly *in my room.*
2. You make sure that my bedroom and my office are always kept neat, in particular, that the desk is available *to me alone.*
3. You are to renounce all personal relations and refrain from criticising me either in word or deed in front of my children.
4. You are neither to expect intimacy from me nor reproach me in any way.
5. You must desist immediately from addressing me if I request it.
6. You must leave my bedroom or office immediately without protest if I so request.

They divorced shortly after.

**Exam Questions**

Speed of light = 2.998 × 10-8 ms-1; mass of hydrogen-2 nucleus = 3.342 × 10-27 kg

Mass of hydrogen-3 nucleus = 5.004 × 10-27 kg; mass of helium nucleus = 6.644 × 10-27 kg;

Mass of neutron = 1.674 × 10-27 kg

1. [2007][2004][2002][2002 OL][2003 OL][2004 OL][2006 OL][2009 OL]

What is meant by nuclear fission?

1. [2006 OL] Name a material in which fission occurs.
2. [2010] The following reaction occurs in a nuclear reactor:



Identify the element X.

1. [2008]

In 1939 Lise Meitner discovered that the uranium isotope U–238 undergoes fission when struck by a slow neutron. Barium–139 and krypton–97 nuclei are emitted along with three neutrons.

Write a nuclear reaction to represent the reaction.

1. [2010 OL] What type of nuclear reaction occurs in a nuclear power station?
2. Name two parts of a nuclear fission reactor.
3. [2003 OL]

The diagram shows the basic structure of a nuclear reactor.

A nuclear reactor contains (i) fuel rods, (ii) control rods, (iii) moderator, (iv) heat exchanger.

Give the function of any two of these.

1. [2009 OL] Name a fuel used in a nuclear reactor.
2. [2007][2004]

What is the function of the moderator in a fission reactor?

1. [2009 OL] What is the role of neutrons in nuclear fission?
2. [2008]

In a nuclear fission reactor, neutrons are slowed down after being emitted.

Why are the neutrons slowed down?

1. [2008] How are fast neutrons slowed down?
2. [2009 OL] In a nuclear reactor, how can the fission be controlled or stopped?
3. [2004] How do cadmium rods control the rate of fission?
4. [2006 OL] Describe what happens to the coolant when the reactor is working.
5. [2006 OL] What is the purpose of the shielding?
6. [2005 OL][2006 OL] Name a material used as shielding in a nuclear reactor.
7. [2003 OL][2010] What is a chain reaction?
8. [2010] Give one condition necessary for a chain reaction to occur.
9. [2006 OL] Describe how a chain reaction occurs in the fuel rods.
10. [2006 OL] Explain how the chain reaction is controlled.
11. [2009 OL] How is the energy produced in a nuclear reactor used to generate electricity?
12. [2009 OL] Give one advantage and one disadvantage of a nuclear reactor as a source of energy.
13. [2003 OL] Name three types of radiation that are present in a nuclear reactor.
14. [2006 OL] Give one effect of a nuclear fission reactor on the environment.
15. [2008][2010]

Fission reactors are being suggested as a partial solution to Ireland’s energy needs.

Give one positive and one negative environmental impact of fission reactors.

1. [2005] Distinguish between radioactivity and fission.
2. [2005] Give an application of fission.
3. [2006 OL] Give one precaution that should be taken when storing radioactive materials.
4. [2005 OL] In Einstein’s equation *E = mc2*, what does *c* represent?
5. [2008] 100 MJ of energy are released in a nuclear reaction. Calculate the loss of mass during the reaction.
6. [2010]

The following reaction occurs in a nuclear reactor:



Calculate the mass difference between the reactants and the products in the reaction

1. [2007]

Nuclear power generation could increase from three hundred gigawatts today to one thousand gigawatts by the year 2050, saving the earth from 1.5 billion tonnes of carbon emissions a year.

* 1. How much energy is generated worldwide every minute by nuclear power today?
	2. At present, why is a fission reactor a more viable source of energy than a fusion reactor?

**FUSION**

1. [2006] Distinguish between fission and fusion.
2. [2003] [2008 OL] What is meant by nuclear fusion?
3. [2007][2009 OL] What is the source of the sun’s energy?
4. [2005 OL] How does the sun produce heat and light?
5. [2006]

The core of our sun is extremely hot and acts as a fusion reactor.

Why are large temperatures required for fusion to occur?

1. [2006]

In the sun a series of different fusion reactions take place. In one of the reactions, 2 isotopes of helium, each with a mass number of 3, combine to form another isotope of helium with the release of 2 protons.

Write an equation for this nuclear reaction.

1. [2006]

Give one benefit of a terrestrial fusion reactor under each of the following headings:

* 1. fuel; (b) energy; (c) pollution.
1. [2006]
2. Controlled nuclear fusion has been achieved on earth using the following reaction.



What condition is necessary for this reaction to take place on earth?

1. Calculate the energy released during this reaction.

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**Exam solutions**

1. Nuclear Fission is the break-up of a large nucleus into two smaller nuclei with the release of energy (and neutrons).
2. Uranium, Plutonium.
3. Krypton
4. 
5. Fission
6. Fuel rods, control rods, shielding, moderator, coolant.
7. Fuel rod: source of energy

Control rod: controls the speed of the reaction by absorbing neutrons

Moderator: slows down neutrons

Heat exchanger: transfers heat energy

1. Plutonium or uranium.
2. To slow down fast neutrons to facilitate fission.
3. To make the nucleus unstable which causes fission.
4. Only slow neutrons can cause (further) fission.
5. They collide with the molecules in the moderator.
6. Dropping the control rods absorbs the neutrons and prevents further fission.
7. They absorbed neutrons which would otherwise cause fission.
8. It gets hot.
9. It prevents radiation from escaping and harming humans.
10. Lead, concrete.
11. It is a self-sustaining reaction where fission neutrons go on to produce further fission (giving more neutrons) etc.
12. The mass of fuel present must exceed the critical mass / at least one of the neutrons released must cause fission of another nucleus.
13. A neutron is fired into the material and this splits the nucleus of one of the atoms releasing more energy and neutrons. This process then continues.
14. The control rods can move up and down and when they are lowered they absorb the neutrons which prevents further fission.
15. The energy produced is converted to heat. This is used to generate steam which drives a generator.
16. Advantage; abundant fuel / cheap fuel / no greenhouse gases / no global warming , etc.

Disadvantage; risk of nuclear contamination / fallout / difficulty of dealing with waste / dangerous, etc.

1. Alpha, beta and gamma.
2. It can cause pollution due to nuclear waste.

Positive: no CO2 emissions / no greenhouse gases / no gases to result in acid rain / less dependence on fossil fuels.

Negative: radioactive waste / exposure to radiation / potential for major accidents etc.

1. Radioactivityis the breakup of unstable nuclei with the emission of one or more types of radiation.

Nuclear Fission is the break-up of a large nucleus into two smaller nuclei with the release of energy (and neutrons).

1. Generating electrical energy, bombs
2. Store in lead or use a tongs when handling.
3. The speed of light.
4. E = mc2  m = E/c2  m = (1 × 108) / (9 × 1016) = 1.11 × 10-9 kg.
5. (300 x 109)(60) J or 18,000 gigajoule (per minute) or 1.8 × 1013 J
6. Easier to initiate reaction, fission can be more easily controlled.
7. E = mc2

m = 3.6 × 10-28 kg

1. Nuclear Fission is the break-up of a large nucleus into two smaller nuclei with the release of energy (and neutrons).

Nuclear Fusion is the combining of two small nuclei to form one large nucleus with the release of energy.

1. Nuclear fusion is the combining of two small nuclei to form one large nucleus with the release of energy.
2. Nuclear fusion
3. Through nuclear reactions.
4. Nuclei are positively charged so enormous energy is required to overcome the very large repulsion.
5. 

Fuel: plentiful / cheap

Energy: vast energy released

Pollution: little (radioactive) waste / few greenhouse gases

1. Very large energy/temperature is necessary.
2. Mass of reactants = 8.346 × 10-27 kg: mass of products = 8.318 × 10-27 kg
loss in mass /defect mass = 2.8 × 10-29 kg
E = m c2
E = (2.8 × 10-29)( 2.998 × 108)2
E = 2.52 × 10-12 J



