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UNDERSTANDING

NUCLEAR ENERGY

An Assoc. of Liberal Democrat Engineers & Scientists booklet

FOREWORD

On 1st August 2011 there were 440 commercial nuclear reactors operating in 29 countries in the world with a total capacity of 376,511 MW supplying 14% of total global electricity. 62 more reactors were under construction in 14 different countries with 154 more planned. 75% of France's, and almost 30% of the EU's electricity comes from nuclear. Reactor design and operating performance continues to improve and '4th generation' designs based on thorium are being researched which could have several advantages.

The first commercial nuclear energy station in the world was built in the UK at Calder Hall. It began supplying electricity in 1956 and operated for almost 50 years.

However, though some stations have already reached the end of their useful lives, the use of nuclear energy has never been free from opposition. Linked to nuclear weapons, it continues to be opposed on a number of grounds, primarily over the perceived millenia-long hazard of dealing with radioactive waste. Even so the industry was making a slow recovery following the Chernobyl explosion as governments realised how difficult it would be to reduce their CO_2 emissions without a substantial nuclear component. Then in March 2011 a tsunami knocked out the standby cooling systems at 4 of the 6 Fukushima 1 reactors in Japan and 3 countries have now reversed recent pro-nuclear decisions.

Opinions have always fallen into 3 main camps. The first believes nuclear energy to be adequately safe and clean, if more expensive than fossil fuelled stations. The second believes nuclear power is dangerous and the long term hazard of the waste is so great it would be unforgivable to add to it with additional power stations. The third believes that the world will have difficulty finding enough alternatives fast enough and that, though undesirable, nuclear energy is better than accelerated global warming.

This booklet seeks to tell the nuclear energy story 'warts and all' and present the facts in as honest a way as possible.

Nothing in this booklet should be taken to imply that campaigns to use energy more efficiently should not be pursued with vigour, nor that renewable sources should not be developed as far and as fast as is sensible.

Cover picture: Nuclear fuel rods being lowered into a reactor. Note the minimal level of protective clothing required

UNDERSTANDING NUCLEAR ENERGY

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1. The Present Position

A short history

By the turn of the 20th century it was known that all material was made up of small particles called atoms. Work at Cambridge by Rutherford in 1908 and Chadwick in 1932 showed that the atom itself contained a nucleus made up of protons and neutrons surrounded by electrons which whizzed around it like planets round the sun. Different atoms contain different numbers of protons and neutrons and larger atoms are less stable than smaller ones. Uranium, which has 92 electrons, 92 protons and usually 146 neutrons, is the largest atom. Electrons have little weight so the ‘atomic weight’ of a particular atom is the sum of the protons and neutrons, in this case 92 + 146, or 238. The chemical shorthand is U^{238}.

The number of neutrons in an atom can vary and the variations are called isotopes. The shorthand for a uranium atom with only 143 neutrons is U^{235}. U^{235} is so unstable that it can split by itself in a process called fission.

In 1919 Rutherford conducted an experiment which demonstrated that atoms could be changed - the alchemists’ ultimate dream! He bombarded nitrogen atoms and detected an oxygen isotope. In 1932 Cockcroft and Walton split a lithium atom. In 1938 two scientists in Berlin, Otto Hahn and Fritz Strassmann, caused fission by accident (Note 1) but it was a third scientist, Lize Meitner, who realised the significance.

In nuclear reactors, fuel rods made of U^{238} and U^{235} are bombarded with neutrons. The U^{235} nuclei split into two and, because smaller nuclei have proportionately fewer neutrons than larger ones, 2 or 3 neutrons are expelled. Some go on to split more U^{235} atoms, so starting an accelerating chain reaction. Smaller nuclei have lower ‘binding’ energies than large ones, so huge amounts of energy are released. Depending on the mix of U^{235} and U^{238}, one tonne of uranium can produce the energy of 70,000 tonnes of coal. A modern station with 1000 MW capacity operating for 80% of the time needs only about 4 tonnes/year.

The first controlled fission reaction took place at Chicago University in 1942 in the middle of World War 2. The destructive potential of the discovery was immediately obvious. It led to the Manhattan project and the first and only offensive use of nuclear weapons, by America on Japan, in August 1945.

The Attlee government, recognizing that leadership of the post war world would fall to those carrying the biggest ‘sticks’, decided to develop its own nuclear deterrent. Calder Hall and Chapelcross power stations were built to produce the weapons grade material.

Some claim that promoting civil nuclear energy was only ever a ‘front’ to produce plutonium but in the 1940s, ‘50s and 60s the only other way to produce electricity was from coal and there were continual struggles to mine enough coal (Ref 1 and Note 2) and increasing concerns about the sulphurous smogs from burning it. Nuclear, which seemed to be an extremely clean alternative, had much to recommend it.

The nuclear programme

Construction of Calder Hall started in 1953 and the first commercial nuclear generated electricity was supplied in 1956, one year ahead of the Americans. In all, 11 Magnox stations (so called after the magnesium oxide cladding used for the fuel rods) came on stream between 1956 and 1971 but only Wylfa remains working today. The average working life has been 37 years (see Table 1). They worked well although maintenance problems and consequent shut downs increased with age. In 1964 a switch was made to so called Advanced Gas-cooled Reactors (AGRs). 7 AGR stations were built. All continue to generate electricity at present. Though closures were originally planned from 2011 to 2023, lives of 4 of the first 5 to close have been extended by 5 years and Sizewell B may go on until 2055.

Unhappily the AGR construction programme was a shambles. Design changes (Note 3) and site militancy caused huge delays. Dungeness B for example started in 1966 but the second reactor only came fully on stream in 1989. Costs rose and operation proved troublesome in the first years.

While the UK chose AGRs the rest of the world chose the simpler Pressurized Water Reactor (PWR). Eventually, in January 1981, the UK turned to PWRs with an application for a 1200 Megawatt (MW) station at Sizewell. An exhaustive 26 month enquiry began in January 1983. Approval was granted in March 1987 and Sizewell B has supplied electricity to the grid since 1995. The Sizewell enquiry was intended to pave the way for 3 further stations: Sizewell C, Hinckley Point C and Wylfa B. Planning permission was actually granted for Sizewell C, which would have been twice the size of Sizewell B, but plans were dropped. In 1998 UK nuclear stations generated 99 TWh or almost 28% of UK electricity but this has dropped steadily since (Note 4).

Station	Type	MW	Start	Status
Calder Hall	4 M’nx	240	1956	D’cm ‘03
Chapelcross	4 M’nx	240	1959	D’cm ‘04
Berkeley	2 M’nx	332	1962	D’cm ‘89
Bradwell	2 M’nx	372	1962	D’cm ‘02
Hunterston A	2 M’nx	338	1964	D’cm ‘90
Hinkley Point A	2 M’nx	660	1965	D’cm ‘00
Trawsfynydd	2 M’nx	580	1965	D’cm ‘93
Dungeness A	2 M’nx	570	1965	D’cm ‘06
Sizewell A	2 M’nx	650	1966	D’cm ‘06
Oldbury	2 M’nx	435	1966	D’cm ‘11*
Wylfa	2 M’nx	980	1971	Gen - ‘12
Hinkley Point B	2 AGR	1140	1976	Gen - ‘16
Hunterston B	2 AGR	1190	1976	Gen - ‘16
Dungeness B	2 AGR	1200	1983	Gen - ‘18
Hartlepool	2 AGR	1245	1983	Gen - ‘19
Heysham 1	2 AGR	1245	1983	Gen - ‘19
Heysham 2	2 AGR	1320	1988	Gen - ‘23
Torness	2 AGR	1364	1988	Gen - ‘23
Sizewell B	1 PWR	1195	1995	Gen - ‘35
Dounreay	1 PFR	250	1974	D’cm ‘94

Table 1: UK Nuclear Programme

Gen - ‘xx = Generating until year 20xx D’cm ‘xx = Decommissioning from year 19xx or 20xx

**One closed Jun 2011, second closing 2012*

The “players”

Calder Hall and Chapelcross were built for the UK Atomic Energy Authority. Thereafter all stations were built for the Central Electricity Generating Board (CEGB) in England and Wales, or SSEB in Scotland. Contrary to popular belief, funds were put aside for decommissioning only to be removed by the then Prime Minister, Margaret Thatcher. When the bulk of the electricity industry was privatised in 1990 nuclear generation was retained in two public sector bodies, Nuclear Electric in England and Wales and Scottish Nuclear in Scotland. In 1996 these two bodies were combined into British Energy and privatised for £1.4bn (half the cost of Sizewell B, but with the government retaining a stake) and given responsibility for running the 7 AGRs and Sizewell B. British Energy has since been sold to the French company EDF with Centrica taking a stake.

The Magnox reactors were initially operated by a temporary public body called Magnox Electric, then by British Nuclear Fuels Ltd (BNFL). Since April ‘05 the reactors, and all other ageing nuclear establishments, have been owned by the Nuclear Decommissioning Authority (NDA) and BNFL has turned itself into a contractor to the NDA and other nuclear clients at home and overseas.

It supplies and re-processes fuel. It operates THORP, the Thermal Oxide Reprocessing Plant at Sellafield, though this is to close, and has overseas business in management and decommissioning.

NIREX, previously the Nuclear Industry Radioactive Waste Executive, was set up in 1982 by the nuclear generators to construct and operate land based facilities to dispose of nuclear waste. Possibly due to the imperative of defence, or mere complacency, no serious attention was given to the safe disposal of this waste until a Royal Commission report in 1976. Indeed, until 1983, much 'Low Level Waste (LLW) and some 'Intermediate Level' (ILW) was simply dumped in the sea. The public opposed every site considered for ILW until NIREX was driven back to Sellafield where public opinion was more favourable. The application for a trial however was refused by the government in 1997 but interest has been re-awakened recently. NIREX too now comes under the NDA.

Of the other main players, the most important is the NII, the Nuclear Installations Inspectorate, a specialist division within the Health and Safety Inspectorate, responsible for licensing every nuclear installation. More recently an Office of Nuclear Development has been set up to oversee the UK's future nuclear programme.

2. Energy from the Atom

Obtaining the fuel

Uranium is as common as tin and more common than gold or silver. It occurs all over the world and in vast quantities in the oceans though in dilute form. Rock containing the ore (pitchblende) is mined like any other mineral. Concentrations above 0.1% uranium are economic at a price of £50/kg while some Canadian ores contain 20%. There are sufficient reserves at £50/kg for over 50 years at current use. Economic reserves would double at £70/kg.

The ore is not particularly radioactive. The main mining hazard arises from the presence of radon gas, a product of uranium decay, which requires good venting of enclosed spaces, for example in houses built over the naturally radioactive granite outcrops in Cornwall. In 2006 44% of all uranium came from Canada and Australia. Australia has 24% of world reserves.

Uranium, which is made up of 99.3% U^{238}, 0.7% U^{235} and a trace of U^{234}, is extracted from the ore (pitchblende) using nitric acid to form 'yellow cake'. It is converted first to uranium tetrafluoride (UF_4) and then uranium, or to UF_6 for enrichment using centrifuges and conversion to the more efficient uranium oxide fuel. The 'carbon footprint' for mining, processing and transporting the fuel is low because its energy is much more concentrated than, for example, coal.

The fuel, either in pure or oxide form, enriched (up to about 5% U^{235}) or not, is machined into rods and clad in protective metal such as stainless steel or Magnox, a magnesium alloy. In a PWR 40,000 rods will be used at a time, each about 1 cm diameter, and 4 m long. Fuel rods can be transported by train or lorry. The total weight of fuel rods needed for Sizewell B is a little over 100 tonnes/year. None of these processes are hazardous (see cover).

The reactor

Reactor design is relatively simple. Fuel rods have to be inserted and regularly replaced. Fission must be initiated and 'moderated' to make the process work. (Neutrons are emitted from U^{235} at such high speed they 'bounce off' other atoms, rather than splitting them. Moderators slow the neutrons down). The heat generated must be drawn off to raise steam to drive turbines and generate electricity in the same way as coal or gas. A shield is needed to absorb radiation and ensure containment lest something goes wrong: monitoring devices, are required to prevent it doing so.

UK reactors are very safe. They include substantial 'redundancy', ie duplicate systems and equipment. All modern reactors are designed to shut down if they should stray outside the safe envelope.

Detailed designs vary. The Magnox reactors use natural uranium fuel. CO_2 gas circulates in channels which run through the reactor to transfer the heat. Graphite (the kind of carbon in pencil lead) acts as moderator and boron rods (which can be lowered or raised within the reactor) used to soak up surplus neutrons and so control the rate of fission. The first Magnox reactors were enclosed within steel pressure vessels about 20 m diameter and up to 100 mm thick.

AGR reactors are more efficient than Magnox ones because they use enriched uranium fuel and operate at higher temperatures (over $600^{o}C$). They, like the later Magnox reactors, have thicker, pre-stressed concrete shields. PWRs are different. Enriched fuel is used, but water at very high pressure acts as combined moderator and coolant. The latest reactors burn fuel at 70,000 MW-days/tonne, about twice the rate of older ones, and run hotter.

The process

Once fission begins, the U^{235} atoms in the fuel rods keep splitting until, after 2-4 years, the heat being generated by individual rods begins to die away. Used rods contain about 96% of uranium, (mostly U^{238} but including up to half the original U^{235}), 1% Pu^{239} (plutonium) coming from U^{238} which has gained a neutron; and 3% of waste products particularly Strontium 90 and Caesium 137. It is the 3% that is highly radioactive.

The spent rods cool at the power station for about 3 months (longer for new reactors) before being moved by train in large 'flasks' 50 -110 tonnes in weight, carrying 2 -5 tonnes of used rods each.

Waste products

The rods go to Sellafield where the reuseable U^{235} is separated from the U^{238}, the Plutonium, and the waste products. The U^{235} and some Pu is re-processed (re-cycled) and the U^{238} or so called 'depleted' uranium used for artillery shells or stored.

The waste products are concentrated into sludges leaving a dilute waste stream to discharge to the Irish Sea. The sludges are classified High Level Waste (HLW) and stored in liquid form under water in stainless steel tanks. A vitrification plant was built in 1991 so HLW can now be dried to a powder (which reduces the volume to one third), dissolved in molten glass, and poured into stainless steel containers where it hardens. The containers are placed in an air cooled store where they will remain for 50 years until they can be disposed of with the Intermediate Level Waste (ILW).

The plutonium poses problems. After separation most is converted to the safer oxide form PuO_2. Some PuO_2 can be used in Mixed Oxide fuel (MOX) which contains 5-8% PuO_2. PWRs can burn 30% MOX, though this isn't yet done at Sizewell. Until 1994 it was hoped to get rid of the plutonium by burning it as PuO_2 in fast breeder reactors (see section 4).

Discharges to the Irish Sea are dispersed via ocean currents. Environmental standards have risen considerably since WW2 and the radioactivity is now about 1/100th that in the 1970s. Indeed more radioactivity arises from fertilizer plant effluents to the Irish Sea than from Sellafield. Even so radioactivity is easy to detect and traces of Technetium have been found in fish caught off the Norwegian coast though this poses no health risk. Improvements continue to be demanded, even though the same money spent on, say, employing more medical staff in the NHS, would bring greater health benefits.

ILW is made up of the fuel rod cladding materials, contaminated equipment and waste from the treatment processes. It is defined as emitting more than 4 gigabecquerels (GB) per tonne of alpha activity or 12 GB/t of beta and gamma, but is not heat generating (Note 5). It is mixed with concrete and stored in steel drums in a purpose designed above ground store. By 1994 the volume of ILW was about 60,000m^3, equivalent to an area 200m x 200m, 1.5m deep. By 2030 the volume will have increased to about 150,000m^3 (2). It is this for which a deep rock store is required.

There is dispute whether recycling the reusable U^{235} in the used fuel rods gives an environmental gain. It reduces the quantity of uranium mined and the volume of HLW, but increases both ILW and discharges to sea. Moreover there is no means of using all the Pu at present.

The greatest volume of waste is LLW, eg paper towels, protective clothing and lab equipment. Its radioactivity is similar to that occurring naturally in rocks in parts of Cornwall. It is packed into steel skips and buried (with waste from hospitals and research establishments) in clay lined trenches at Drigg, 4 miles south of Sellafield. In future it will be compacted and stored in containers in a concrete vault the size of 12 football pitches.

Decommissioning

At the end of their safe working lives, external buildings can be demolished quickly but the reactors themselves retain radioactivity. Although de-commissioning has begun and techniques are being developed to speed progress, total removal is likely to take 100 years. The reactor material will then be classified ILW. Because it has to be included in the total ILW, the final amount would only reduce by 10% if nuclear generation ceased immediately (2).

Final disposal

Though other ideas have been considered, the consensus view is that ILW should be placed in a deep rock store which would be monitored for leakage. Originally it was planned to be eventually sealed off but more recently it has been suggested it could be kept open in case some could be recycled. The Swedes have had a small rock store at Forsmark since 1988 whilst the French filled one shallow store at Centre de la Manche between 1969 and 1994 and are currently filling a second at Centre de l'Aube. In both countries only short lived ILW (which decays to LLW in 300 years), not long lived ILW, is buried. The Americans plan to store waste in the Yucca Mountains, Nevada and the Finns have begun work on the Onkala waste repository, near Olkituoto.

A similar store in the UK could open by 2050 if a planned test facility opens by 2025. 3 councils in Cumbria have shown interest in providing a site. It will take around 1000 years for the radioactivity to reduce to naturally occurring ores. The choice of site needs to take into account changes in groundwater levels, siesmic activity and even breakdown of civil administration (though in the latter event, ILW waste would be one of the lesser problems). It would probably be 300 metres deep to avoid potential glacial action. Such a store could not 'explode' but could be a source of radiation if some geological problem arose.

3. The Safety Issues

What is safe?

Safety is relative. Each day 1 in about 1.5 million people in the UK dies from an accident or catching an infectious disease. Even today nearly 1 in 10,000 women in the UK dies from her pregnancy - a risk,

incidentally, about 5 times greater than from taking the contraceptive pill.

On a relative basis nuclear energy is exceptionally safe. There have been no known deaths in the UK from explosion or radiation. Because nuclear energy is safer than most alternatives, its use can be said to have saved lives.

When the nuclear energy programme was started the principal alternative was coal. Coal's history has been punctuated by regular mining accidents including the tragic slagheap slip at Aberfan. There have been premature deaths from lung diseases amongst miners and the general population. Indeed one study (3) concluded that chronic bronchitis (mostly caused by coal burning) was responsible for 15,600 premature deaths in England and Wales in 1981 alone.

Even so an anxiety about nuclear energy remains. The public does not understand the concept of 'relative risk' and 'thresholds' and anti-nuclear campaigners play on this by publicising any suspicion of danger however trivial. Nuclear energy also gets caught in what can be called the '2+2=5' syndrome. If 2 or 3 unusual illnesses occur it is tempting to assume the nearest factory chimney, overhead power line - or nuclear energy station - must be the cause. In consequence the environment suffers because money is diverted from more beneficial causes.

Understanding radiation

Mankind has lived with radiation since time began. Mild doses do not harm (Note 5). So long as the dose is not heavy damaged cells recover. (This is the strategy behind radiotherapy which can not avoid temporary collateral damage to healthy cells as it focuses on cancerous ones). Radioactive isotopes are regularly ingested to assist medical diagnosis and X-rays are common.

In any case, as Table 2 shows, nuclear energy contributes only 0.1% to UK radiation levels. In fact radiation near *coal* stations can be high because coal contains trace elements including uranium which are not controlled (Note 6). The highest levels are near the re-processing plant of Sellafield, where the additional dose is about 150 microsieverts or 'units' a year which compares with 2200 units/year arising naturally from the area, and up to 7800 units/year occurring *naturally* in some areas of Cornwall. Simpler comparisons can be made. The average radiation received by UK citizens from nuclear energy is <3 units/yr, which compares with 150 received on a return flight to the Far East or 50 from a chest X-ray. For many years it was believed *any* radiation was dangerous but Canadian work reported in 1998 (4) and the BBC Horizon programme of 13 July 2006 suggested low levels are actually beneficial! It is thought that radiation, at some lifetime level below 100,000 units, activates genes responsible for protecting against cancers, in different but similar ways to vaccinations.

Source	%	Natural/ Man Made
Radon gas	50	N
Gamma from soils + rocks	14	N
Eating, drinking, breathing	11.5	N
Cosmic from outer space	10	N
Medical (Xrays etc)	14	M-M
Fallout from weapons	<0.2	M-M
Occupational	0.3	M-M
Consumer products	<0.1	M-M
Nuclear energy discharges	0.1	M-M

Table 2: Breakdown of radiation, by source (5)

Chernobyl etc.

A nuclear reactor cannot explode like a nuclear bomb but can explode physically if badly designed or mismanaged. The first nuclear incident and the only significant one in the UK occurred in an air cooled pile at Windscale in 1957 used for producing plutonium. The graphite moderator caught fire and burned for 4 days before being brought under control. The release of radioactivity was limited by filters, but Strontium 90 from that incident can still be traced in aquifers and older people's bones.

In 1979 safety mechanisms failed to detect low coolant levels at the Three Mile Island reactor in the USA. The reactor overheated and there was confusion amongst the experts. Fortunately control was recovered before the containment vessel failed.

In 1986 one of the 4 reactors at Chernobyl was subjected (ironically) to a safety test to find out how long the cooling systems would work if electricity was cut off. To sustain the test all other safety systems had to be temporarily disconnected. Even without the benefit of hindsight such a test sounds imprudent. On the 26th April the reactor exploded sending radioactive dust into the atmosphere which, due to the prevailing winds at the time, fell across much of Western Europe.

There have been many intensive studies of deaths and sickness caused by the explosion. Though some estimates have been very high, WHO (6) concluded in 2005 that, despite a high incidence of thyroid cancer in young children in the worst affected area, less than 50 deaths so far can be directly attributed to the explosion, 3 immediately and about 28 more after a few weeks. WHO also estimated that 4000 others (about half from workers rushed to the scene to contain the radiation) might die prematurely from cancers caused by the additional radiation exposure. This figure depends on small fractions being multiplied by large numbers and may be reduced by improved cancer therapies. In addition 2,800 sq km of land around Chernobyl was contaminated and 135,000 people and 35,000 cattle had to be moved. Even Welsh sheep were moved between pastures before being killed for meat.

What surprises many however is that the 3 other reactors at Chernobyl continued to operate, the last one closing only in December 2000. Moreover removing the human population from the restricted area reduced man associated wildlife such as rats and pigeons and allowed a resurgence of species like bison, boar, wolves and otters. 270 species of bird have been recorded and there are calls for the area to become an international wildlife reserve! It is particularly re-assuring that studies have shown <u>no</u> genetic damage in the local fauna.

Fukushima

On 11th March 2011 the 6th largest eathquake ever recorded occurred off the east coast of Japan generating a tsunami wave 14 metres high. The wave overtopped the tsunami defences (designed only for a 5.7 m high wave) swept 12,690 to their deaths, left 14,700 more unaccounted for, 117,570 buildings damaged and another 14,606 completely destroyed. (8th April estimates). The grid electricity failed. Hundreds of thousands were left homeless with lives and livelihoods wrecked. One estimate put the insurance cost at £200 bn. Despite the horror of this tragedy it had largely disappeared from the newspapers within 10 days.

Instead reporters focussed on the nearly 40 year old reactors 1-4 at the Fukushima 1 nuclear power station. Here the earthquake caused only minor damage but the tsunami flooded the reactor basements knocking out the standby diesel generators. These were needed to maintain the cooling system if the grid electricity failed. The reactors had to be shut down. As noted on page 7 even fully used fuel rods give off heat and need cooling. Temperatures in the fuel rods, the core and the cooling water all rose. Despite attempts to cool the reactors by spraying and flooding the building the fuel rods in reactors 1-3 partially melted and some steam from the cooling system escaped. Pressures rose and some steam converted to hydrogen which exploded blasting holes, not in the reactor but the external building. A little radioactivity escaped with the steam but more escaped with the external cooling water which eventually had to be discharged to the sea. People were evacuated from a 30 km exclusion zone, vegetables dumped and the Japanese economy was disrupted due to loss of electricity. Reactors 1 to 3, which were close to the end of their working lives,

will be abandoned. Fukushima was not as serious as Chernobyl. The reactor did not explode and the spread of radiation was much less. The consequence was principally economic. There was no loss of life.

The main lesson to be drawn from the above incidents and 55 years of nuclear energy generation is that concerns over health and threat to life are overemphasized. We do not stop flying for example when a plane crashes. Nuclear energy worldwide has cost fewer lives, caused less illness, and done less damage to the environment per unit of electricity than coal, probably oil, and possibly gas. (Note 7). In the '80s in the UK 50 miners were still being killed every year, 500 dying prematurely from mining related diseases and many more in the general population.

Plutonium theft and terrorism

Another anxiety linked to nuclear energy is theft of plutonium used in nuclear weapons. Bombs can be made from either U^{235} or plutonium with plutonium more efficient and only 5kg needed. The Hiroshima bomb contained 60kg of enriched U^{235}.

Plutonium becomes critical (ie fission starts automatically) in quite small quantities so needs careful handling. UK stocks are large and growing. By 2010 the UK held 5% of global stocks (c. 100 t) with 67% in the separated (and safer) PuO_2 form. Most is 'locked into' MOX or used rods. One needs more than 'back of a garage' processing to produce weapons grade plutonium but there is a risk. Unfortunately it is much easier to obtain plutonium from the old USSR countries than the UK. (See also Note 8).

The bombing of the World Trade Centre in 2001 led some to suggest nuclear installations are similarly vulnerable. This overstates the problem. Nuclear reactor shells are necessarily much more robust than buildings. In any case danger comes from radioactive dust thrown into the atmosphere by some triggering explosion, not radiation from a cracked reactor or a drum of waste lugged from a store. In reality there are many more vulnerable structures and situations for a determined terrorist.

4. The Future

Global position

The number of new reactors being built was barely keeping up with closures, but the need to slow global warming and the threat of rising oil and gas prices gave incentives to reconsider nuclear energy. In the EU, Germany, Belgium and Sweden had resolved to wind down their nuclear industries but in June 2010 the Swedish government voted to replace its existing reactors and both Germany and Belgium were prepared to allow their reactors to continue beyond the previous 32 and 40 year cut off dates in return for extra taxes to fund renewables. Following Fukushima, however, Germany has now voted to close its reactors by 2022, and Italy and Switzerland voted not to restart building programmes. Most other countries are conducting reviews but seem likely to carry on. The Finnish Olkiluoto reactor (now about 3 years late due to problems with foundations and licensing) is slowly reaching completion and the French one at Flamanville, begun in December 2007 (and 20+% over budget and 2 years late), is also progressing with one more, Penly 3, planned. In both Canada and the USA mothballed reactors are being returned to service and, in the USA, 4-6 new ones are likely to come on line by 2018. The Finns saw no other way to meet their Kyoto targets and were worried by their reliance on Russian gas. 62 reactors were under construction in August 2011, 26 in China.

UK position

After years of trying to duck a decision the UK government finally indicated support for new nuclear stations in July 2006. (In the previous 11 years there had been 8 different energy ministers and 3 contradictory energy white papers!). Now EDF have plans to build 4, 1600 MW new reactors, 2 at both Hinckley and Sizewell; Horizon, a joint venture between E.on and RWE npower, have plans for 6000 MW split between Wylfa and Oldbury; and NuGeneration, another joint venture involving GDF Suez and Scottish and Southern have plans for 3600 MW of reactors at Sellafield. It has been agreed that new stations can also be built at the existing nuclear sites of Bradwell, Hartlepool and Heysham. Some preliminary work at Hinckley has begun.

The government expects the private sector to finance construction; provide for all decommissioning through a discrete fund set aside as electricity is sold; and meet the insurance costs for all but the most extreme event. Decommissioning is expected to cost only around 0.5p/kWh but nuclear electricity, though cheaper than most renewables, remains more expensive and less flexible than from coal or gas (reactors take up to a day to come on stream). Current discussion revolves round the carbon 'floor' price, which would increase the cost of fossil electricity, or some other mechanism which would support nuclear if fossil prices fell too low. Of course if fossil stations are required to install CCS (carbon capture and sequestration) nuclear could undercut them easily and profits could be embarrassingly high! A simpler approach would be for the Coalition government to decide what percentage of generation it wants from nuclear and negotiate a price for it rather than leave things to the market.

The first new reactor could be operational in 2018 allowing 2 years for a planning enquiry and for contracts to be set up and 5 years for construction. The leading designs are the French 1600 MW Areva reactor now being built in Finland, France and China and the Westinghouse 1150MW AP1000.

The dilemma

Despite the Rio, Kyoto and Copenhagen summits, the desire for activities that use energy such as travel, heating and air-conditioning, computing and so on in developed countries, and the demand for simple basic facilities in the developing world, shows no sign of diminishing. Global electricity demand has increased over 6 times since 1960. World demand will not reduce: the best is to hope the world will use energy more efficiency and adopt a more environmentally sustainable mix of fuels.

A few years ago there were high hopes for renewable sources of energy. Of these only wind has produced much. Technological and cost breakthroughs are needed in wave, tidal and solar power, and some means to store energy must be found before the variable energy available from wind and solar can provide much more than 10% of UK electricity unless we retain a matching amount of coal or gas. If new stations are not built (planning permission still has to be obtained) fossil fuels will be generating more electricity in the 2020s than they do now.

Nuclear electricity has never been as cheap as from fossil fuel (Note 9) though, despite the apparently high costs of dealing with the waste, it is not as high as some claim. The majority of the much quoted £73bn clear up cost is for weapons making facilities with more for medical and industrial use.

Assuming £30bn is attributable to nuclear electricity, the unit cost, spread over the 3000 TWh or so of electricity generated by existing nuclear stations over their lifetimes (Note 10) is only 1p/unit. Furthermore this money is not all required immediately. About £15bn, invested now, earning 3%/annum interest, would be sufficient. In the 2009/10 year renewable energy was being bought at a premium of about 5p/unit! If 20% of electricity becomes renewable and 5p extra is paid for each unit (it is likely to be more, not less), the renewable subsidy would be £4bn/year

(£100 bn in 25 years) - many times the clean up cost of nuclear.

The cost of new nuclear power stations depends on whether one or several are built but the European Commission has stated that nuclear is the cheapest low carbon source with the minimum carbon footprint equalled only by onshore wind.

Fast breeders, Thorium

Nuclear technology continues to develop but still uses uranium inefficiently. Known reserves should meet demands for the 3rd generation of nuclear reactors (7) but something better is needed beyond that. The fast breeder reactor programme at Dounreay had two objectives. First to research processes which would multiply uranium reserves 50 times. Second to find a way to use the Plutonium produced from conventional reactors and weapons grade Pu released by disarmament programmes.

A 60 MW pilot reactor, *of domestic washing machine size,* used fuel enriched to 75% U^{235}. Commissioned in 1959, it produced its design output in 1963, supplying electricity to the grid until 1977. From 1975 to 1994 a prototype commercial reactor using MOX with about 20% Pu and a design output of 270 MW was successfully demonstrated but this was expensive and it remains cheaper to use uranium inefficiently in PWRs.

There is 4 times more thorium than uranium. The Th^{232} isotope is not itself fissile but, bombarded with neutrons, it will transmute to U^{233}. The fissile process needs acceleration but thorium reactors are claimed to be intrinsically safer with less toxic waste. Thorium is used in the 220MW Kakrapar-1 reactor in India, which has plentiful thorium and a 300 MW prototype is under construction there. China is also active. Thorium reactors are not yet as economic as uranium ones but current small scale UK research should be supported.

Fusion

Nuclear energy currently relies on splitting a large atom. Enormous quantities of energy can also be obtained by fusing small atoms together and changing 'matter' to energy - Einstein's 'relativity' insight. Fusion is the reaction which occurs within the sun and gives earth its warmth. Fusion occurs when a mix of 2 different types of hydrogen deuterium (H^2) and tritium (H^3) are heated to exceptional temperatures - at least 10,000,000 ^{o}C. At this point the atomic structure breaks down and the separate particles form a 'soup' or plasma. Super-cooled magnets are used to hold the plasma in suspension. If this can be done for more than a fraction of a second some of original deuterium with 2 neutrons and tritium with 3 convert to helium with 4, with the lost neutron changed to energy. Fusion has been studied for 40 years and progress made. South Korea's KSTAR reactor has achieved 10,000,000^{o}C and 0.8 seconds of plasma. In mid 2009 tenders were invited for the bigger International Thermonuclear Experimental Reactor (ITER) to be built at Cadarache in France. The ratio of energy in to out has now reached 1.0 and there is confidence that this will be the last step before commercial use becomes possible though that may still be another 30 years away. The UK's contribution to the research is about £20m/year, plus a capital contribution.

5. Conclusions

With hindsight

There is no doubt that the post war decision to generate some electricity from nuclear energy rather than coal, saved lives and gave health and environmental benefits. It is true that initial environmental standards (as others in different fields) needed tightening and that it was wrong not to plan for long term disposal of waste from the beginning.

Nuclear electricity proved to be more expensive than expected and more than fossil fuels, though these did not carry the environmental costs of their emissions via some kind of carbon tax (Note 11). On the other hand, despite Chernobyl and Fukushima, it is clear that nuclear energy remains remarkably safe.

Policy and consequences

Though rarely presented in this way, phasing out nuclear energy would mean more fossil fuel stations (and greater global warming than would otherwise be necessary) probably using the newly discovered shale gas reserves in USA and Europe. Both the Labour and Coalition governments have decided the perceived hazards from nuclear generation are less worrying than faster global warming and the probable costs lower than most renewables or coal and gas with CCS. They have perhaps been surprised how much more difficult it has been to bring substantial renewables on line despite the targets and incentives on offer.

There is no absolute reason why new nuclear stations should crowd out renewables. This is a political decision. Frankly, we need all the low carbon supplies we can get. A new generation of nuclear stations however would 'buy time' while scientists and engineers struggle to find more ways to remove the threat from global warming.

Notes

Note 1 - Meitner, Hann and Strassman

They were bombarding uranium with neutrons trying to make it heavier

Note 2 - Shortage of coal

For example, following severe cold weather in January 1947, coal supplies to power stations were rationed. Electricity was cut off during certain hours, factories closed, and nearly 2 million people put out of work for 3 weeks

Note 3 - Design changes

Nuclear energy is a highly specialised market. CEGB, in a bid to stimulate competition, gave contracts to 3 companies and ended up with a multiplicity of designs.

Note 4 - Share of electricity supplied

UK 2009: Nuclear 18%, Gas 45%, Coal 28%, Renewables 7%, Other 1%, Imports 1%. Renewables include hydro, wind and biomass stations such as energy from waste plants though not all of this counts as 'renewable'. The 1% imports are mostly nuclear from France. Scotland's electricity was half nuclear.

Note 5 - Radiation and radioactivity

Radiation is the transfer of energy. It 'radiates' from the sun, other sources in the cosmos or natural or man made sources here on Earth. Radiation travels at different wavelengths with the shorter ones, X-rays and gamma rays, being the most penetrative and harmful though longer ones like ultra violet can cause skin cancer and infra red, burns. Radioactivity releases gamma rays and also alpha and beta particles. Alpha particles are slow moving helium nuclei which can be stopped with a sheet of paper. Beta particles are smaller and faster and can be stopped by aluminium foil. Both carry electrical charges and are referred to as 'ionizing' radiation. The electrical charge makes them hazardous because, if ingested, they will seek out something to combine with and may damage tissues within the body. (*Naturally* occurring radon gas is dangerous for the same reason). Gamma rays (which bombard us from space and, from time to time, the sun) are much faster but barely ionizing. They can only be stopped by lead or concrete shields several inches thick.

Note 6 - Radiation at coal fired stations

Coal contains traces of uranium. The amount of uranium fed into and discharged from coal fired power stations can be as much as 1% of that fed to a PWR as fuel. This ends up on slag heaps or in land fill without controls.

Note 7 - Pollution from oil and gas.

Eg. Torrey Canyon, 120,000 t. oil spill off Lands End, 1967; Amoco Cadiz, 223,000 t. oil spill off Brittany, 1978; Exxon Valdes, $15bn damage off Alaska 1989; Piper Alpha, oil + gas rig, 167 lives lost; Sea Empress oil spill from Milford Haven, 1996, BP's Bluewater Horizon 2010. Of other man made disasters, probably the worst is the 1984 Union Carbide disaster in Bhopal which killed 6000 and left up to 500,000 suffering

Note 8 - Plutonium risks

Another suggested risk is that PuO_2 powder could be dispersed by conventional explosives and inhaled. However it would be easier and more dangerous to disperse a bacterium such as E. Coli 157 this way.

Note 9 - Before privatisation the cross subsidy from fossil fuel generation to nuclear was hidden within the CEGB and SSEB accounts, as was the fund for decommissioning. At privatisation, British Energy purchased 8 stations including Sizewell B for a mere £1.4bn. These were only profitable because most debt had been written off. Between 2002 - 04 electricity prices fell as Ofgem squeezed generating capacity out of the grid. The foolish decision to disregard the higher costs of CO_2 free nuclear meant it became effectively bankrupt and had to be bailed out by the taxpayer.

Note 10 - Total electricity generated

DECC statistics give the total electricity generated by nuclear stations between 1970-2009 as 2,278 TWh. The figure between 1956-69 has been estimated as 50% of the installed capacity listed in Table 1 which totals 111 TWh and from 2010 to 2035 at 60% of remaining capacity which gives 652 TWh. The total is 3,041 TWh. It will be more if Sizewell or other AGR stations have their lives extended

Note 11 - Carbon tax

A carbon tax of £10/tonne of carbon would add 0.22p to each unit of electricity produced from coal and 0.09p from each unit produced from gas. It would raise about £1.8bn in tax if applied to carbon released from all sources. Currently carbon is being traded at c. £12/tonne under the EU Emissions Trading Scheme (EU ETS).

References

1. "Attlee", by Kenneth Harris

2. House of Lords Select Committee on Science and Technology 3rd Report "Management of Nuclear Waste"

3. "Power Production - What are the Risks" Study by JH Fremlin 1987

4. Quoted by Dr David Hall in an article "Who's afraid of radiation" published in LM Archives at http://www.informinc.co.uk/. The study looked at breast cancer rates in 32,000 women who received chest x-ray fluoroscopy for tuberculosis. Small doses apparently had a beneficial effect. Another study compared lung cancer rates with average radon levels across 1729 US counties (90% of citizens) and found an inverse relationship (New Scientist 14.3.98)

5. National Radiological Protection Board. Study done in 1991.

6. "Chernobyl's Legacy: Health, Environmental and Socio-Economic Impacts" published by the Chernobyl Forum Sept 2005. (The Forum is made up of WHO and 7 other UN agencies)

7. "World Energy Outlook to 2100". Presentation given by Michael Jefferson to the Institution of Civil Engineers on 28.9.1994 and "Briefing: Prospects for nuclear power" by Stuart Dagnall. Proc. Institution of Civil Engineers Energy 160, Feb 2007 pps 3-8

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