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ENGLAND'S ATOMIC AGE
STRATEGY ON THE HISTORIC INDUSTRIAL ENVIRONMENT REPORT

DESK TOP INVESTIGATION AND ASSESSMENT

PART 1

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ARCHAEOLOGICAL
SURVEY AND INVESTIGATION

ENGLISH HERITAGE

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England's Atomic Age

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Dungeness power station (c) W D Cocroft

When history look back at the twentieth century she will see science and technology as its theme; she will find in the monuments of Big Science - the huge rockets, the high energy accelerators, the high flux research reactors - symbols of our time just as surely as she finds in Notre Dame a symbol of the Middle Ages.

Alvin Weinburg, Director Oak Ridge National Laboratories, USA

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1 PREFACE

This report forms one of a series of Strategy on the Historic Industrial Environment Reports (SHIERs) produced for the English Heritage Industrial Archaeology Strategy Group. This set of reports aims to provide succinct national overviews of particular industries to inform English Heritage policy and conservation strategies. They will also be useful to a wide range of interested parties, such as local authority Historic Environment Record officers and others concerned with studying, managing and recording historic resources.

The report has been compiled as a desk-top study, although informed by past visits by the author to a number of nuclear installations. It is primarily concerned with England's nuclear facilities, but recognises that the nuclear industry is a national concern and passing reference is made to facilities in Scotland and Wales.

It complements an earlier report on *Electric Power Generation* produced for English Heritage's Monuments Protection Programme (Trueman 1994), which considered all forms of electricity generation excluding nuclear.

Part One of the report gives a brief overview of England's nuclear installations beginning with a short history of early atomic research, the post-war quest to develop nuclear weapons and the subsequent development of the civil atomic energy programmes. The technology of the industry is described and the broad functional relationships between the different locations are discussed. Brief descriptions are also given of the main reactor types and the principal types of buildings that will be found in nuclear power stations and their impact on the wider landscape.

Part Two of the report provides advice on the formation of a national strategy for the future management and stewardship of the resource. This section also presents an analysis of the survival, protection and conservation of nuclear installations in England.

2 INTRODUCTION

In Britain, the early post-war decades were characterised by a period of dynamic industrial renewal, underpinned by optimism and faith in a brighter industrial and social future that could be delivered by scientific and technological progress. Beyond their practical benefits the development and exploitation of new technologies, such as nuclear energy, were also seen to embody national prestige and pride. Politically this optimism was tempered by the loss of empire, the search for a new role in the world and the threat posed to the country by the Soviet Union and her allies. The history of Britain's nuclear industry during this period is of national and international importance.

The growth of Britain's nuclear industry illustrates many of the themes of the advanced technological industries of this era, including the dominance of the state through its early and continuing association with the defence of the country. The development of the nuclear power programme promised a flow of electricity that would be so cheap that metering would be unnecessary. It was also seen as a clean power source in a country that was reliant on coal for electricity, heating and rail transport and a capital that was periodically cloaked in smog. As with many other areas of scientific advancement during the post-war period Britain was a world leader in nuclear technology, exemplified by specialised research establishments and new power stations.

The history of the nuclear industry also typifies changing public attitudes to the benefits of scientific advancement, from the differential respect for expert opinion of the 1950s to the mistrust that today characterises much public discussion about scientific development. This unease with the nuclear industry grew through the 1980s, following the Three Mile Island, United States, accident in 1979 and the 1986 reactor disaster at Chernoybyl, Ukraine. The industry's early close association with the country's nuclear weapons programme has also led people to question its morality and has fed fears about its safety, and more recently its vulnerability as a target for terrorist attack.

Over the next decade most of Britain's post-war nuclear infrastructure will be closed and decommissioned. This is taking place at a time when there is intense debate about the effects of global warming caused by the burning of fossil fuels. This has in turn sparked renewed discussion about the possibility of building a new generation of nuclear power stations. A decision will also be required within the next few years about the future of the United Kingdom's nuclear deterrent. This historical over view of the industry is both timely in documenting the demise of what may be the first phase of this industry, and in contributing to the wider debate about the future of the nuclear industry.

3 A SHORT HISTORY OF BRITAIN'S NUCLEAR PROGRAMMES

The beginnings

The modern study and understanding of the atom is barely a century old. In the last decade of the 19th century major advances were made across Europe that laid the foundations of modern atomic physics. Some of the most significant included, Wilhelm Röentgen's demonstration at Würzburg, Germany, in 1895 of the ability of x-rays to pass through solid matter. Around the same time in Paris Henri Becquerel observed the phenomenon of photographic plates being fogged by streams of particles produced by uranium and a few years later Pierre and Marie Curie announced that they had separated radium from pitchblende (Clark 1980, 9-10). In 1905, Albert Einstein published his special theory of relativity and his well-known equation $e=mc^2$, which proposed that enormous amounts of energy were stored within matter.

Figure 1
Cambridge, The Cavendish Laboratory, by W M Fawcett 1874, many of the most influential nineteenth and early twentieth century physisicts worked in this building and in 1932 in its cellars the atom was split, listed grade II
© English Heritage

In Britain, during the late 19th and first part of the 20th centuries, the Cavendish Laboratory, in Free School Lane, Cambridge, occupied a leading position amongst Europe's scientific centres and was one of the most influential places for research into atomic physics. It was housed in a purpose-built laboratory, designed by W M Fawcett and opened in 1874, with extensions by the same architect in 1896 and 1908, and a further addition in 1936. It is listed at Grade II (Figure 1). Physicists working in this building were responsible for some of the most important advances on atomic theory of their age. In 1897, Professor Joseph John (JJ) Thomson demonstrated that cathode rays were in fact negatively charged streams of particles, which he called 'electrons'. Two years previously he had been joined by the New Zealander Ernest Rutherford, who was to transform the concept of the atom. Early ideas about the form of atoms imagined them as solid balls; by the beginning of the 20th century an atom was commonly conceived as resembling a plum pudding, where the electrons were the plums (Cathcart 2004, 5). In 1911, Rutherford, by then at the University of Manchester, revolutionised this model by proposing that an atom was not solid but comprised a nucleus surrounded by electrons. This theory was further refined in 1913 by the Danish physicist Niels Bohr, who conceived of a simple model of a hydrogen atom (*see* Figure 21) of an electron orbiting its nucleus and is a theory that remains useful today (Nuttall 2005, 30).

Rutherford continued to be fascinated with the properties of the atom and after his return to the Cavendish as its director in 1919 he single-mindedly pursued this theme. By the late 1920s John Cockcroft, directed by Rutherford, was investigating the structure of the atom and if it might be possible to artificially disintegrate or split the atom. The final successful outcome was achieved through combination of factors. Atomic theory was advancing rapidly at this time and in particular the work by the Russian Georgii Gamow pointed the way forward for Cockcroft. New laboratory equipment was also required, including a means of stepping electricity up to very high voltages. Here the laboratory was able to draw on work by the large electrical manufacturers who were beginning to design equipment for long distance power transmission. The transfer of technology from the large industrial concerns was aided by close personal links between the laboratory and Metropolitan-Vickers (Cathcart 2004, 259).

In 1930 and the following year early experiments to split the atom were unsuccessful and work was temporarily interrupted by a reorganisation of the laboratory. This allowed Cockcroft and his new assistant, Ernest Walton, to re-erect their apparatus in a far larger room that had previously been used as a lecture theatre. This new equipment cost around £500 and was at the time the most costly device the laboratory had purchased. With this apparatus in April 1932 it was found by bombarding a lithium target with artificially generated protons they were able to observe the lithium with a mass of 7 occasionally absorbing a proton and the resulting nucleus with a mass of 8 breaking down into two helium nuclei. They had split the atom. In this pioneering atmosphere earlier in the same year the existence of the neutron had also been confirmed by James Chadwick (Clark 1980, 28-9). Success had been achieved through the advances in atomic theory, the availability of new laboratory equipment, and the scientific community at the Cavendish led by the driving force of Rutherford.

This was an important achievement for British science but the physicists at the Cavendish were acutely aware that other groups might also be close to this goal. Prior to the Great War, British, French, German, and to a lesser extent Russian scientists had dominated the field. With the continent in disarray in the aftermath of the war, during the 1920s Britain dominated the field of nuclear physics; however, as the decade advanced its lead was pursued by a number of centres in Europe and increasingly in North America. As in many areas of scientific endeavour the researchers regarded themselves as part of an international community and reported on their latest discoveries in freely accessible scientific publications and exchanged knowledge through personal contacts, visits, symposia and conferences. In Berlin in late 1938, Otto Hahn and Fritz Strassmann observed that uranium bombarded with neutrons produced radioactive isotopes (Clark 1980, 43-4). They didn't fully appreciate the significance of their discovery but described it to their former colleague Lise Meitner, an Austrian and now a refugee from the Nazis living in Sweden. She in turn discussed the discovery with her nephew Otto Frisch, also a physicist, who coined the phrase 'fission' to describe the phenomenon. The experiment was reported in early 1939 and was quickly replicated in many other laboratories (Gowing 1987, 8-9). In April, the Joilet-Curie team in Paris were the first to publish and to recognise that not only fission fragments and energy were produced but also enough neutrons to maintain the process. Later in the year, as German forces were poised to invade Poland, on I September the Dane, Niels Bohr, and the American, John Wheeler, published a joint paper, noting that fission was far more likely to occur in uranium 235 atoms rather than the more common uranium 238 atoms.

The Second World War

The development of the atomic bomb during the Second World War represented a remarkable scientific, technological and industrial achievement, from the theoretical understanding of atomic structure developed during the late 1930s to the dropping of the two atomic bombs in 1945. It and other wartime developments including defence electronics (in particular radar and computing) and the jet engine would all have profound effects on the post-war world.

In 1940, the British government was first alerted to the possibility of an atomic bomb in a memorandum 'On the construction of a super bomb' written by two émigré scientists Otto Frisch and Rudolph Peierls. They argued that 5 kg of uranium 235 would have the equivalent explosive power of thousands of tons of dynamite, in addition to the deadly effects of radiation. They also proposed a method whereby uranium 235 could be separated. The government's response was to appoint the MAUD Committee under George Thomson (Imperial College, London) to investigate the feasibility of developing an atomic bomb during the present war. This committee reported in July 1941 that it might be possible to produce a bomb using uranium 235 and possibly plutonium, it also discussed the possible peaceful uses of atomic energy to produce power (Gowing 1987, 14). In September Winston Churchill, advised by the Chiefs of Staff, decided to proceed with the development of an atomic bomb, but perhaps with little conception of the scale of the undertaking required. One of the few companies that had the capabilities and resources to embark on such a programme was Imperial Chemical Industries (ICI) (Reader 1975, 287-93). They had been involved in initial discussions from as early as June 1940 and were very keen to develop the technology partly through a sense of national duty but also with regard to the future development of atomic energy. The Scientific Advisory Committee Defence Services Panel rebuffed their approach, the government wishing to retain control of the development. Sir John Anderson, Lord President, became the minister in charge of the project, which was administered by the Department of Scientific and Industrial Research under the cover name of the Directorate of Tube Alloys.

Within ICI by June 1944 the government had authorised the expenditure of £975,000, of which £870,000 had been spent. This represented nearly two thirds of the government research carried out in ICI to June 1944, a company that through its production of chemicals and explosives was crucial to the war effort. It was, however, insignificant compared to the $2.2 billion spent by the United States on its atomic bomb programme - The Manhattan

Figure 2
Rhydymwyn, Clywd, July 1997, during the Second World War building 45/P6 housed ICI's experimental isotope separation plant © Peter Bone

Project (Hughes 2002, 97), which was in turn more than four times the amount the Germans spent on the V2 rocket programme (Neufeld 1995, 273). The greatest proportion of the British government's money was spent at ICI Billingham, Stockton-on-Tees, within the General Chemicals Group, and lesser amounts within other groups. Other ICI plants known to have been involved in the work include its Metals Division at Witton, Birmingham and the poison gas filling factory, at Rhydymwyn, Clywd (Clark 1980, 119). At the latter site an experimental isotope separation plant was built. This work was conducted in a reinforced concrete framed structure, with a parabolic concrete roof and walls in-filled with brick (Figure 2). Internally this provided a large open double-storey space, only interrupted by the columns supporting the roof. It is uncertain if this structure was specially constructed for the purpose, or adapted from a building intended to be used in the production of mustard gas shells. The achievements of ICI atomic research during the war are obscure, as their official historian W J Reader notes the 'paper records were either destroyed or swallowed by official secrecy' (Reader 1975, 293).

Britain's lead in this field was also assisted by the arrival of two French scientists from the Joilet-Curie team in Paris, Hans von Halban and Lew Kowarski. They brought with them the world's entire stock of heavy water. It may be used as a moderator in an atomic pile that is it has the effect of slowing the passage of neutrons, thereby making a collision more likely. The significance of this shipment is realised by the prediction in the 1939 Bohr and Wheeler paper that a slow neutron reaction with uranium 235 will create a new element – plutonium (Gowing 1987, 14). The French team was initially housed in the Cavendish Laboratory in Cambridge, and were then moved to Canada, first to Montreal and then to Chalk River, Ontario (Gowing 1987, 17). There the first reactor outside of the United States was constructed, the knowledge acquired there aiding the British, Canadian and French post-war nuclear programmes (Clark 1980, 130).

A number of scientists in the United States were also considering the theoretical possibility of constructing an atomic bomb. As in Britain many of the leading nuclear scientists were European émigrés, who were both aware of nuclear research in Germany and of the dangers it might pose. Leo Szilard was so concerned that in 1939 he wrote a letter to President Roosevelt, to give it more credibility he arranged for it to be signed by Albert Einstein.

Initially there was scepticism on both sides of the Atlantic that an atomic bomb could be constructed that might be of use in the current war and of a size that could be delivered by an aircraft. In summer 1940, an important British scientific mission headed by Henry Tizard visited America to discuss recent developments in military technology. Nuclear fission and the world's uranium stocks formed only a very small part of these talks, reflecting the doubts in the minds of leading scientists, such as John Cockcroft, that a viable weapon would be achievable in a few years. One outcome of these exchanges was the establishment of an office of the United States National Defense Research Committee (NDRC) in London. A member of this mission, Kenneth Bainbridge, was given special permission to attend meetings of the top secret MAUD Committee. Through this contact he began to be conscious of a distinct shift of British scientific opinion that a bomb might be feasible. Reports by Bainbridge to his superior, Vannevar Bush, informal contacts between British and American scientists, and the publication of the final MAUD report, all helped to convince Bush that the United States government should expand its nuclear research programme (Zimmerman 1996, 151-3; 188-9). The MAUD report was officially handed over to the United States in October 1941, and shortly afterwards George Pegram and Harold Urey were sent to England to learn about the work being carried out on uranium (Smyth 1945, 30-1).

At this early stage the United States would have welcomed the development of a joint project, but as the Americans quickly pushed ahead British scientists found themselves excluded from key areas (Gowing 1987, 16). In September 1942, General Leslie Groves was placed in charge of the atomic bomb project, known as the Manhattan Project, at Los Alamos, New Mexico. The Quebec Agreement signed between Britain and the United States in 1943 allowed British scientists some access to the project, on an understanding that it wouldn't be used against a third party without mutual consent and agreed the joint exploitation of uranium supplies. It was also from this point that many of Britain's scientists working in this field moved to join the United States programme.

Post War

The immediate post-war history of the British nuclear industry and research was dominated by the government's wish to develop firstly an atomic bomb and secondly a hydrogen bomb.

The bomb programmes

On 8 January 1947, a small secret cabinet committee, known as Gen 163, within the Attlee government took the decision that Britain should proceed with the development of the atomic bomb (Hennessey 2003, 44-49). The team put in charge of developing Britain's atomic bomb was led by William Penney, a physicist and a leading member of the wartime British Mission to the United States' Manhattan Project that was responsible for creating the first atomic bombs. Penney played a prominent role in the project, in addition to his scientific contributions, he also sat on the Target Committee, which discussed which Japanese cities should be attacked, and flew with the mission that dropped the bomb on Nagasaki to film its results (Norris *et al* 1994, 19). Responsibility for the British bomb project was given to a specially created division of the Armaments Research Department (ARD). To disguise its real function it was known as Basic High Explosive Research (BHER), its title usually abbreviated to HER, which functioned as a secretive and autonomous section of the larger organisation. Initially, the team comprised 34 ARD scientists, a figure that quickly grew to a few hundred; its activities were initially split between a defence research centre at Fort Halstead, Kent, and the Royal Arsenal, Woolwich.

Research facilities

In June 1947 to support this work part of the Shoeburyness range on Foulness Island, Essex, was transferred from the ARD to the HER project (Figure 3). Following the acquisition of the range its development to meet the needs of HER became an urgent and national priority, and existing plans drawn up by ARD were modified to meet the needs of HER. For the next decade the establishment was continuously developed to support the growing demands of the atomic and later hydrogen bomb projects (Cocroft 2004). It became the principal centre for investigation of the development of conventional explosives used in nuclear weapons. The research conducted there fell into two main areas: investigation of the physics of explosives, and simulation of the effects of nuclear explosions. This work acquired greater significance after the 1963 Limited Test Ban Treaty, which prohibited tests in the atmosphere, outer space or under water. There is no completely accurate

Figure 3
Foulness, Essex, the entrance to the main administration building at Foulness, built in 1949, it was here that Sir William Penney worked on his visits to Foulness © English Heritage BB99/15966

Figure 4
Foulness, Essex, air blast tunnel used in the simulation of blast waves © English Heritage BB99/15990

way of simultaneously mimicking all the consequences of a nuclear explosion, though the four principal effects (blast, heat, radiation and electro magnetic pulse) can be simulated individually or sometimes in combination. The main concern at Foulness was with replication blast and heat effects for which specialised facilities were constructed (Figure 4).

At Fort Halstead the HER project initially operated in a fenced-off enclosure of existing buildings, some new test facilities were built but it is not known if they still survive. It was only with the decision, in autumn 1948, that the team should manufacture the radioactive components of the bomb that a new base was sought, and not until the following year that a wartime airfield at Aldermaston, Berkshire, was selected. It was developed both for nuclear weapons research and for manufacturing radioactive components. For the first tests disc-like billets of plutonium were received from Sellafield, Cumbria, and taken to a special 'hot' laboratory (designed to handle radioactive materials) where they were cast into blanks before being machined into the two interlocking hemispheres and gold plated to prevent corrosion, together they formed they formed the core of the bomb. Today, around 4,500 people are employed at Aldermaston covers 880 acres (356 ha), and has around 1000 densely packed buildings, split into at least eleven functional areas: some are standard office accommodation, but others are specially designed research and manufacturing structures (Hawkings 2000).

Figure 5
Orfordness, Suffolk, 'Pagodas' used for the testing of the non-fissile components of nuclear weapons © English Heritage AA021750

In 1954 discussions also began about the location of test facilities for vibration and shock testing of warheads to simulate the types of stresses they might experience in an aircraft's bomb bay. Given that a safety radius of 550 yards (503m) was required around the test structures no suitable location was available at Foulness (NA:PRO ES1/269). For these reasons a second range was developed on a remote shingle spit at Orfordness on the Suffolk coast (Kinsey 1981). Its association with armament experiments dated back to the Great War, and during the 1930s it was also briefly connected with the development of radar. The AWRE occupied the site from 1953, at first working on the ballistics of the bomb casing for the Blue Danube warhead and later on the physical stresses the bomb experienced before detonation. To support this work a series of concrete and shingle test chambers were erected: some had rigs for testing resistance to vibration, while in others the extremes of temperature encountered during flight were simulated. Although there was no fissile material, these massive structures were designed to absorb accidental detonation of the conventional explosive elements of the bomb (Figure 5). Other specialised structures included camera booths for recording weapons in flight, centrifuges for studying 'G' forces on bomb components, a rocket sled track, and control rooms where the results of experiments were remotely recorded. After Blue Danube research continued on new warhead and bomb casing designs, some required further development of the site, such as the new centrifuge building E1 erected during the early 1960s to support the Polaris programme. By the end of that decade most of the work was transferred to Aldermaston, which was also equipped with Pagoda-like structures, and atomic weapons research at Orfordness ended in 1971. The National Trust now owns the former AWRE area.

The AWRE also had short associations with two other locations in Cornwall and in Cumbria. In the late 1950s negotiations began on a nuclear test ban treaty, if it was to be successful methods needed to be devised to monitor any unauthorised explosions. One method of detecting nuclear explosions is by measuring the seismic signal produced by an underground explosion. While the talks were proceeding an American scientist raised the possibility that the seismic effect of an underground explosion might be 'decoupled' by detonating the explosive charge in an underground cavity. If their effects could be disguised or hidden it might have serious consequences for the verification of any moratorium on nuclear tests. The AWRE was set the urgent task, known as Operation Orpheus, of ascertaining if this theory was correct. For the experiments a disused mine at Callington, Cornwall, was acquired and another at Glenrriding, Cumbria. Tests were carried out in 1959 and 1960, the mines were then abandoned. Most of the modifications carried out for these trials were destroyed by the test explosions, although some remains of cable trunking and ventilation equipment have been found at Callington (www.subbrit.org.uk). Seismic monitoring for verification purposes is today based at Blacknest Lodge, West Berkshire, which is linked to a number of remote instrument stations, some of which were located in former Royal Observer Corps underground monitoring posts.

Production facilities

To meet the demands of the bomb programme large industrial scale plants were also required and a Production Division was established in February 1946 under Christopher Hinton, with its headquarters in a redundant Royal Ordnance Factory at Risley, Cheshire. Other sites were then quickly acquired to build production facilities. In September 1947, at Sellafield, Cumbria, on the site of a wartime TNT factory, construction began of the Windscale piles, reactors at that date being known as atomic piles (Figures 6). Pile No.1 went critical in October 1950 followed eight months later by Pile No.2. Their main purpose was to produce weapons grade plutonium, along with smaller amounts of polonium-210

Figure 6
Windscale, Cumbria, 1954, the Windscale Piles and the ten-storey reprocessing plant used to extract plutonium, rising from which is a single tall ventilation stack © Crown copyright. NMR G5158-1

that was used as an initiator in some British bombs. The choice of technology for these piles was dictated by the need to produce plutonium as quickly as possible (Gowing 1987, 21: Arnold 1995, 8-10). To ensure their speedy entry into service the pragmatic solution appeared to be to recreate the tried and tested technology of the wartime United States Hanford Piles. They used natural uranium fuel, with a graphite moderator and were water cooled. One serious draw back of this system was that water loss, or failure of the water pumps, could result in a catastrophic accident. In contrast, the early British experimental piles at Harwell, Oxfordshire, BEPO and GLEEP, were both air cooled (*see* below). This method was thought to be inherently safer and was chosen for the Windscale Piles. A mark of the urgent necessity to bring this plant into operation was the positioning of the filters on the top of the air coolant chimneys rather that at their bases. The filters were included in the design at the insistence of the physicist Sir John Cockcroft and as a result became known as 'Cockcroft's galleries' (Figure 7). Also at Sellafield, a ten-storey separation plant

Figure 7
Sellafield, Cumbria, to the left are the cooling towers of Calder Hall power station, to their right are the Windscale Piles, which Lord Hinton referred to as 'monuments to our original ignorance', in the foreground is the dome of the experimental Gas Cooled Reactor © W D Cocroft

was built to extract the plutonium and facilities for plutonium purification and final finishing in to metal billets.

At Capenhurst, Cheshire, another wartime Royal Ordnance Factory, a gaseous diffusion plant was constructed to produce highly enriched uranium. Manufacture of uranium fuel rods for the reactors was established at Springfields, Lancashire, a former poison gas factory. To the north of Risley, at Culcheth, another site was acquired that was later occupied by the Safety and Reliability Directorate, this site has been cleared. Other components for the bomb were made at the Royal Arsenal Woolwich and Chatham dockyard, while ROF Chorley, Lancashire (an explosives filling factory) manufactured some types of specialist production machines.

Figure 8
Windscale, Calder Bridge (later Calder Hall) Cumbria, April 1954, work underway on the PIPPA reactors, to the right are the Windscale Piles © Crown copyright.NMR G5074-3

Windscale alone was unable to manufacture enough plutonium for the 200 atomic bombs Britain envisaged producing by the late 1950s. The next generation of reactors would be dual-purpose Magnox reactors producing both plutonium and electricity, these reactors were initially known as PIPPAs. At Sellafield, adjacent to the Windscale site, work began on the first pair of pair of PIPPA reactors in August 1953 (Figure 8), and in 1955 it was decided to build an additional pair at Sellafield and four more at Chapelcross, Dumfrieshire (Arnold 1995, 21). These reactors were graphite moderated and cooled by carbon dioxide, the fuel was held in magnesium alloy cans that were able to withstand far higher temperatures than the earlier aluminium containers. The name of these containers, MAGNOX, gave its name to this fleet of reactors. The first in this series, known as Calder Hall, was opened by the Queen in October 1956. A year later, after a serious fire in Pile 1the original Windscale piles ceased production (Arnold 1995). Until 1964 Calder Hall and Chapelcross were operated to optimise the production of military grade plutonium, after this date, with perhaps an exception of a period during the late 1970s, they have been run on a civil fuel cycle that does not produce weapons grade plutonium (Norris *et al* 1994, 23, 27, 76-8).

From about 1954 a former Royal Ordnance Factory at Burghfield close to Aldermaston was redeveloped for warhead manufacture, assembly and inspection. Coincidental with the introduction of the British H-bomb, around 1960, two new warhead assembly buildings, linked to ancillary structures by closed corridors, were constructed. They were specially designed to contain the risk from an explosion during assembly, their concrete domed roofs, of steel mesh covered by sprayed concrete, being designed to minimise the risk from flying debris. Around the outside is loose gravel which would fall in to smother any explosion (hence the domes are colloquially known as the 'Gravel Gerties'). Architecturally they are almost identical to United States' nuclear weapons final assembly plant at Pantex, Carson County, Texas (Tredici 1987, Plate 12).

In the early 1960s, AWRE took control of another former wartime munitions factory at Llanishen, Cardiff. Its function was to produce high precision and complex components for nuclear weapons, including parts of the bomb's core that used a mixture of uranium^{238} and beryllium (Norris et al 1994, 73-76). AWE Llanishen ceased operations in February 1997 and the site is being cleared for new uses.

Aldermaston and Burghfield remain at the centre of the maintenance of Britain's nuclear deterrent and in July 2005 it was announced that over the next three years £350m per year will be spent on upgrading their facilities (Ministry of Defence Press Notice 146/2005).

United Kingdom Atomic Energy Authority

In October 1945, only a few months after the Second World War had been ended by the dropping on the two atomic bombs on Japan the British government gave the go ahead for the creation of a nuclear research and development centre. The site chosen was a former RAF airfield at Harwell, Oxfordshire. Here some of Europe's earliest reactors were constructed, GLEEP (Graphite Low Energy Experimental Pile) was commissioned in August 1947 and a year later BEPO (British Experimental Pile) went critical on 3 July 1948. At first the focus of its work was on supporting the development of an atomic bomb and BEPO was initially used to produce small quantities of plutonium for research purposes.

In 1954, the United Kingdom Atomic Energy Authority (UKAEA) was established by the Atomic Energy Act, with its headquarters at Harwell, its main role was as a research and development organisation to design and build pioneering reactor types. It was also responsible for buying, processing and reprocessing uranium, these activities which had been handled by the Production Division became the responsibility of the Industrial Group of UKAEA.

UKAEA was responsible for the development of new reactor types and the advancement of nuclear technology. To support this experimental work throughout the 1950s and 1960s new structures were added to the Harwell campus. Alone it was too small for all of the research facilities that were needed and new out stations were created. The most well-known of these was at Dounreay in the north of Scotland with its distinctive spherical reactor dome. The uranium fuelled Magnox stations were seen as first generation nuclear technology, one of the goals during the 1950s was the development of fast reactors. These reactors would operate without a moderator and using fast neutrons would manufacture their own fuel. To test this technology on an industrial scale at Dounreay UKAEA developed a 14 mega watt fast reactor which was operational by 1959. By the 1970s a much larger 250 mega watt experimental fast reactor had been added. UKAEA also developed the next generation of power stations based around improved Magnox technology, using enriched uranium fuel, a graphite moderator and gas cooling. In October 1958, within a separate enclave at Windscale construction started of a pilot Advanced Gas Cooled Reactor (AGCR) plant. It was commissioned in 1961 and by 1963 was supplying electricity to the National Grid (Arnold 1995, 24).

In the late 1950s, on a green field site at Winfrith, Dorset, a new establishment was set up primarily to study the operation of reactor experiments and small prototype systems. From the late 1950s UKAEA had also been exploring the production of energy by nuclear fusion, as opposed to nuclear fission that is used in the present generation of nuclear power stations. This is thought to be the process that produces the sun's energy and would offer a practically limitless and waste free energy source. At Harwell a Zero Energy Thermonuclear Assembly was installed in one of the hangars. As this line of research also required larger facilities and in 1960 UKAEA acquired a former Royal Naval Air Service airfield at Culham, Oxfordshire. This research is so complex and costly that in the early 1980s 14 nations combined to build the Joint European Torus (JET). This is the world's largest fusion research machine; it comprises massive D-shaped magnets 4 metres high and 2.5metres across, which are used to create a magnetic containment field (Close 1990, 37-45). Agreement has recently been achieved that the International Thermonuclear Experimental Reactor (ITER) will be built in France at a projected cost of £6.7 billion (Lichfield 2005, 27).

In industry, radioactive isotopes are widely used to measure the thickness of plastic and metal sheets by the amount of radiation they can stop; they are also used to study corrosion and wear and to monitor various processes. They are equally widely used in medicine for diagnosis, therapy and research. Although some isotopes were produced at Harwell a dedicated factory, The Radiochemical Centre was established at Amersham, Buckinghamshire. This remained part of UKAEA until 1971 when it became the The Radiochemical Centre Ltd, later Amersham International plc and is now known as Nycomed Amersham plc.

The Atomic Weapons Research Establishment (AWRE) was also involved in the development of the civil nuclear programme. On its Foulness range experiments were undertaken in the 1950s and 1960s to proof test reactor containment vessels and other components. At the same time at Aldermaston due to the cancellation of a number of weapons systems there was some spare capacity that could be employed on nuclear power programmes. In support of the development of the Prototype Fast Reactor, a demonstration plant was built in building A50 and the specification developed for a fuel production plant at Windscale. This work also included the manufacture of fuel pins for reactors. Civil projects continued until 1973 when AWRE was transferred to the Ministry of Defence (Hawkings, 2000, 72-4).

Administratively the 1971 Atomic Energy Authority Act split the authority's fuel and isotope production between two publicly owned companies. The fuel business passed to British Nuclear Fuels Ltd (BNFL) with sites at Capenhurst, Chapelcross, Windscale and Springfields. The Radiochemical Centre, Amersham, Buckinghamshire, which was responsible for the manufacture of radioactive isotopes became the Radiochemical Centre Ltd and later Amersham International plc and today is known as Nycomed Amersham plc.

The UKAEA remains a world class nuclear research organisation and in addition to its decommissioning responsibilities it is also in charge of the Joint European Torus (JET), Europe's fusion project which it operates on behalf of Euratom at Culham, Oxfordshire.

Small research and training reactors

In addition to the large government research centres industrial companies and universities also maintained relatively small research reactors. These were variously used to develop new manufacturing and diagnostic techniques, atomic research and for training students to work with nuclear reactors. Examples of reactors in this category include a small teaching and research reactor at Newham, Greater London, operated between 1966 and 1982 by Queen Mary College, it has been dismantled and removed. Also in Greater London was a 10 kW reactor named *Jason* that was installed at the Royal Naval College, Greenwich, to train naval personnel in the use of reactors (Edwards 1969, 12-20). At Derby Rolls-Royce have a reactor associated with their nuclear submarine propulsion work. In Scotland, adjacent to the UKAEA's experimental Dounreay site the Royal Navy established a research centre for nuclear propulsion with a small research reactor.

This group of reactors is the most difficult to research and at present it is not possible to provide a definitive list of the locations of all the small research reactors in England. A list of Britain's research reactors identified so far may be found in Appendix E.

The civil nuclear power programmes

Britain's post-war civil nuclear power programme was initially closely related to work on the development of nuclear weapons and it may be broken down into four main phases.

1945-55	Government begins a major nuclear research and development programme, although the initial emphasis was on weapons research
1955-1964	Major civil nuclear power programme
1964-74	Second phase of nuclear stations based on Advanced Gas Cooled Reactor technology
1974	The intention was announced to build a new generation of reactors based on Steam Generating Heavy Water Reactor technology, later cancelled

The beginning of the civil nuclear programme

In February 1955, the government announced (Lord President of the Council 1955) that it intended to embark on a civil nuclear power programme based on the Calder Hall Station, Cumbria - the world's first industrial scale nuclear power station. This programme was designed to provide the country with 1500-2000 mega watts of electricity and was to be delivered over a ten year period at a cost of £300 million. Nuclear power was seen as 'the energy of the future' and as a means of meeting the country's ever increasing demands for electricity. Despite massive investment in modern pits by the National Coal Board, there were grave concerns about the ability of the coal industry to produce sufficient fuel for the power stations, not least through concerns about labour shortages. This was at a time when coal was used to generate 99 per cent of the country's electricity (IEE 1993, 3). A situation that had prompted a number of coal fired stations to be converted to oil. The risks associated with this policy were, however, highlighted a year later with the Suez Crisis and the resulting threats to the security and costs of fuel imports. One consequence was a revised and enlarged nuclear power programme initiated in 1957, which envisaged increasing the nuclear programme to have the capacity to supply 5000-6000 mega watts of electricity by 1965 (Minister of Power 1957). By 1960, the country's energy situation had improved, coal and oil were more plentiful and supplies appeared to be more stable, new conventional generating stations were also becoming more efficient and therefore cheaper. These factors lead to a scaling back of the nuclear programme, whereby orders would be restricted to one station per year (Minister of Power 1960).

Figure 9
Dungeness,Kent, the 1960s Magnox station
© W D Cocroft

This initial stage of the programme relied on Magnox technology and in total nine Magnox stations were built in the United Kingdom (Figure 9). During this period Britain had a world lead in the development of nuclear energy for civil purposes. One of the economic incentives for developing the nuclear industry was that it would lead to a thriving export trade in reactor technology. This ambition never materialised, although British designed Magnox stations were built at Tokai Mura, Japan and Latina, Italy. Abroad, in the United States there was less incentive to develop nuclear power, given its huge coal and oil reserves

(Radford 1961, 71). France also lagged some years behind Britain and it was not until the mid-1960s that her reactors began to produce substantial amounts of electricity from nuclear power (Hecht 1998, 95).

The second nuclear power programme

The publication of the White Paper *The Second Nuclear Power Programme* (Minister of Power, 1964) marked the beginning of the next phase. This series of power stations was based around improved Magnox technology developed by the UKAEA. The plan called for five twin-reactor Advanced Gas Cooled Reactors (AGR). Construction was shared between a number of contractors which hindered both the accumulation of knowledge and saving that could be made through economies of scale. Design problems delayed the commissioning even further and some of these power stations did not become operational until the early 1980s.

A new generation of reactors

The next stage in the development of the industry came in 1974 when the government announced that the next power station would be a Steam Generating Heavy Water Reactor (SGHWR). This was in contradiction to the Central Electricity Generating Board's (CEGB) wish to use American designed Pressurised Water Reactors (PWR). In January 1978, the decision was taken to cancel the SGHWR programme, and approval was given for the construction of AGR stations at Heysham B, Lancashire (Figure 10) and Torness, East Lothian.

Figure 10
Heysham, Lancashire, the two Advanced Cooled Reactor stations have a combined output of 1320 MWe
© English Heritage NMR 20319-015

In 1979, the government accepted the industry's prediction that a new nuclear power station would need to be ordered every year from 1982. It also announced that subject to the necessary safety controls that the next station would be a PWR. This was to be known as

Sizewell B, Suffolk, and was to be built alongside the existing Magnox station, it was the only PWR station built in England.

Privatisation

In 1989 after forty years in public ownership the electricity industry was split up and privatised. The non-nuclear power stations were sold to four main power generating companies, National Power, Power Gen, Scottish Power and Hydro-Electric, while most of the transmission infrastructure was acquired by the National Grid Company. The original intention had been to include the nuclear power stations in the privatisation, but they were removed due to uncertainties about operating costs and liabilities arising from decommissioning and waste management. Instead all nuclear power stations in England and Wales passed to Nuclear Electric and those north of the border to Scottish Nuclear.

After six years experience of operation in the newly commercialised market, in 1995 the government published its review of the nuclear power industry. This recommended that the older Magnox stations that were coming to the end of their economic lives would remain in public ownership under a new company called Magnox Electric. While a new private sector company, British Electric, would take ownership of the more modern Advanced Gas Cooled reactors and the newly completed Pressurised Water Reactor Sizewell B.

In 1999, BNFL's international business was expanded when it acquired the American company Westinghouse, one of the major global suppliers of nuclear technology (Griffiths 2005, 44). Together they formed the world's largest nuclear fuel reprocessing company, Westinghouse managing the fuel production facility at Springfields, Lancashire. However, in 2005 it was announced that BNFL was to sell Westinghouse, in line with its strategy to be a contractor to the nuclear industry rather than a constructor (Milner 2005, 25).

The Industry in the 21st Century

Today the British nuclear industry provides about 24% of the country's electricity (Nuttall 2005, 26), but by 2020 this proportion is projected to decline to about 7-8% as existing power stations come to end of their productive lives. Current government energy policy, presented in the 2003 Energy White Paper (Department of Trade and Industry, 62) does not contain any proposals to construct new nuclear power stations. It did not, however, rule out the possibility that such stations might be necessary in the future to meet the country's energy needs and its commitment to reduce carbon emissions. Existing nuclear power stations will continue to produce electricity until the end of their planned lives, or longer if their licences are extended.

At present the principal concern of the industry is the decommissioning of redundant power stations and other nuclear installations. In 2001, Ms Patricia Hewitt, Secretary of State for Trade and Industry, announced that the Liabilities Management Authority (LMA) would be set up to oversee the programme of decommissioning of the civil nuclear liabilities held by BNFL and UKAEA (Hansard, 2001 Column 990-995). Its role was to be to provide the strategic direction for the decommissioning programme and take ownership of all of the sites controlled by these organisations. It was also envisaged that it would initially place contracts with the current sites licensees, BNFL, Magnox Electric and UKAEA, to carry out the clean-up programmes at each location. In March 2003, after comments on the White Paper (DTI 2002), the government changed the name of the LMA to the Nuclear Decommissioning Authority (NDA), a statutory non-departmental governmental body; which began its activities on 1 April 2005 (Gore 2004, 10). It has responsibility for 20 sites (*see* appendix C), comprising research centres and power stations, a number of which are still active and are projected to remain so until the end of their operating licenses. At present there are no plans for the NDA to take on the responsibility of cleaning up sites operated on behalf of the Ministry of Defence, although the Energy Bill would allow it to undertake such work at a future date. Also in 2005 the British Nuclear Group (BNG) came into being as the specialist clean-up arm of BNFL.

In 2003, the UK government and devolved administration is Scotland, Wales and Northern Ireland appointed the Committee on Radioactive Waste Management (CoRWM). Its main task is to review the options for managing UK radioactive wastes, for which there are no current agreed solutions. Throughout 2005 it will be holding a series of stakeholder workshops to discuss the options, or combination of options, that might be presented to government in 2006 (CoRWM 2005).

4 The geography of the nuclear industry and its landscape

The bomb programmes

Britain's nuclear industry exhibits a national distribution (Figure 11). Due to the immediate post-war imperative to develop an atomic bomb as quickly as possible former government sites were the preferred locations for the new atomic facilities. Places that were already under government control circumvented any potentially lengthy negotiations about land acquisition. Most also had at least rudimentary services and buildings that might be adapted, they also often had associated accommodation, both for construction workers and later for the new establishments' personnel. The principal part of the atomic bomb development team was based in the existing government research facilities at Fort Halstead, Kent, and the Royal Arsenal, Woolwich. As the programme expanded an establishment was built on Foulness

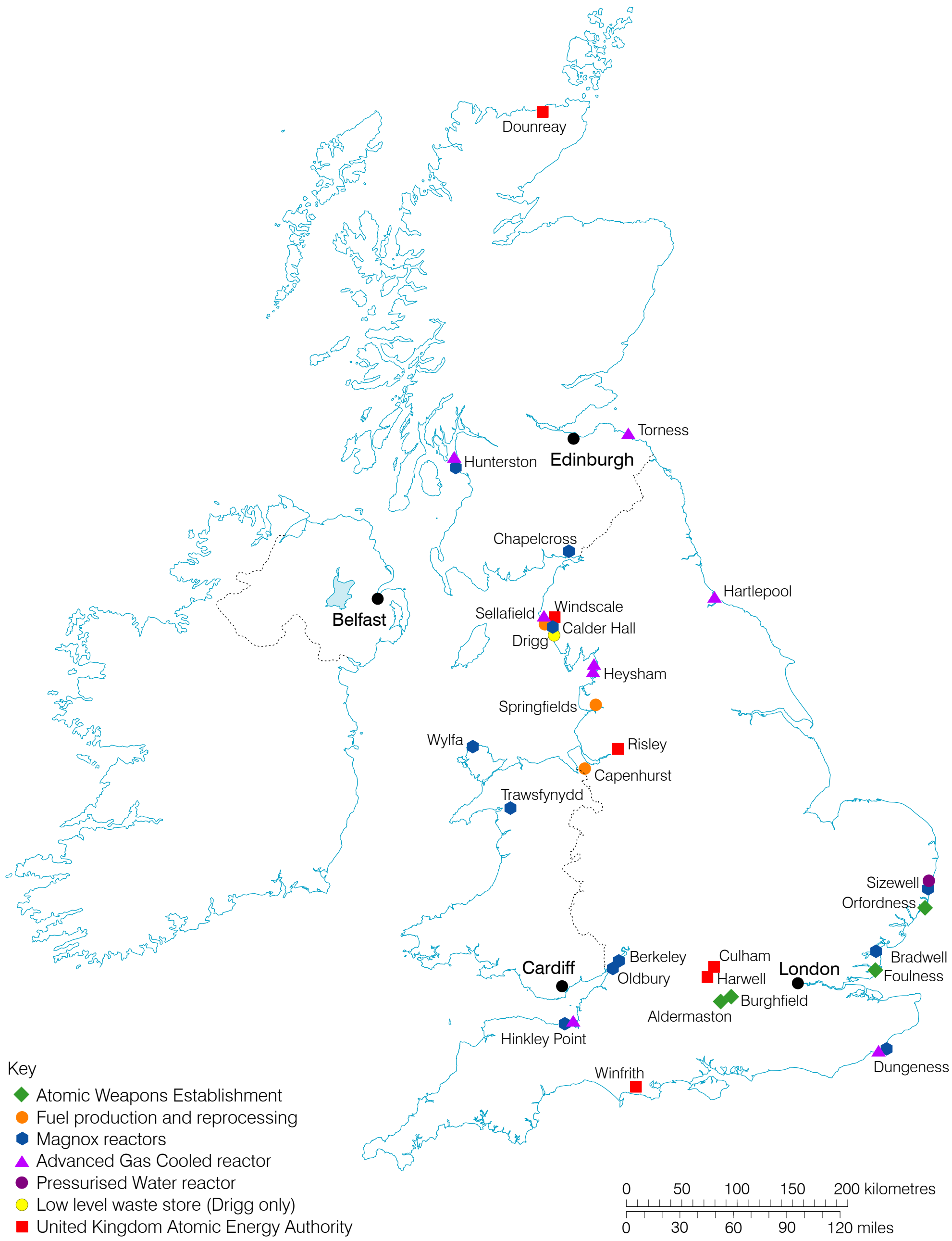

*Figure **11***
Britain's main nuclear installations

Island, Essex, an existing Armament Research Department site, which offered remoteness for trials using high explosives and the necessary secrecy. In 1950, the headquarters of the Atomic Weapons Research Establishment was moved to an abandoned temporary wartime airfield at Aldermaston, Berkshire. It provided a site relatively close to London and other government research establishments and plenty of room to construct the facilities required. To supplement the facilities at Aldermaston, the nearby redundant Royal Ordnance explosives filling factory at Burghfield was acquired and adapted for warhead assembly activities. As the trials work expanded another test site was required and the shingle spit of Orfordness, Suffolk, was developed to test the robustness of warheads during flight. Cut off from the mainland, the shingle spit had been in government hands since the First World War for aircraft and bomb ballistics trials and offered remoteness and secrecy.

In the first decade after the war the main focus of nuclear research activity was closely associated with the production of nuclear weapons. A nuclear research and development centre was established on the site of RAF Harwell, Oxfordshire, a pre-war permanent airfield with many good quality brick buildings. It later became the headquarters of the United Kingdom Atomic Energy Authority and acquired the nearby former Royal Naval Air Service airfield at Culham, which is now used for fusion research. It also developed another site at Winfrith, Dorset, for reactor research, in addition to Dounreay, Caithness, and parts of the Windscale site.

To produce the radioactive components for the bomb the headquarters of the Production Division was established at another former Royal Ordnance factory at Risley, Cheshire. Other wartime factories at Capenhurst, Cheshire, and Springfields Lancashire, were adapted for uranium enrichment and fuel rod manufacture. In Cumbria, the former site of wartime TNT factory was acquired at Sellafield for the construction of the Windscale Piles, which were required for the production of plutonium. By 1959, to the south of Sellafield the site of another wartime TNT factory at Drigg became the location of a low level waste radioactive store. This site is used to store low level waste from a large variety of sources, including industry, research laboratories and hospitals.

The civil nuclear power programmes

The location criteria for the civil nuclear power stations were different to those for the early weapons related sites. Similar to conventional power stations the principal requirement was for the ready availability of large quantities of cooling water, for this reason all the Magnox stations were built in coastal locations, with the exception of Trawsfynydd, Gwynedd, which obtained its cooling waters from an adjacent inland lake. Other factors that needed to be considered included the availability of a large, stable level site free from the risk of flooding, access to the national grid initially to provide the power necessary for construction and reliable potable water supplies for the boilers. Any potential site also needed to allow for relatively easy access for construction traffic, local planning issues and objections by amenity societies also needed to be considered (Gammon and Pedgrift 1962, 139-159). Nuclear power was a new and potentially dangerous technology and coastal sites were also attractive as they were generally remote from centres of population. Locations were also chosen in areas of the country that were regarded as being energy deficient, such as

Figure 12
Dungeness, Kent, the Advanced Gas Cooled Reactor is the right © W D Cocroft

Bradwell, Essex, and Sizewell, Suffolk, where there no local fuel reserves. In most instances the new power stations were built on greenfield sites, although at Calder Hall the prototype station was built within the Sellafield complex and at Bradwell and Chapelcross, Dumfries, stations were constructed on or close to wartime airfields.

The second generation of Advanced Gas Cooled Reactors (AGR) also required access to large amounts of cooling water. The prototype AGR was built by the UKAEA within the Sellafield complex and four of the seven AGR stations were placed adjacent to existing Magnox stations at Dungeness, Kent (Figure 12), Hinkley Point, Somerset, Sizewell, Suffolk, and Hunterston, Ayrshire. The three stations placed on greenfield sites at Hartlepool, Heysham, Lancashire (Figure 13), and Torness, East Lothian were all sited in coastal locations.

Figure 13
Heysham, Lancashire, here the power stations were built on reclaimed land, the Irish Sea providing a plentiful supply of cooling water
© English Heritage NMR 20319-008

New landscapes

Figure 14
Dungeness, Kent, the power station in its landscape
© W D Cocroft

Nuclear installations due to their size have also created distinctive late 20th century landscapes, the research establishments with hundreds of densely packed buildings often surrounded by layers of security fencing. The power station sites are overshadowed by the large rectangular architectural blocks of the reactor buildings and turbine halls which in turn dominate their usually low lying coastal locations and often provide focal points in the landscape for many miles around (Figures 14 & 15). Around many power stations the coastline has often been modified and constantly maintained to prevent erosion. The late 20th century landscape also became a 24 hour landscape and for security and/or production reasons nuclear facilities are illuminated throughout the night when they are even more visible. The impact of the new nuclear installations beyond their boundary fences was often more than visual; the local environment is also dominated by the noise of the power station,

Figure 15
Bradwell, Essex
© English Heritage

announcements from Tannoy systems and the hum of machinery. Beyond the power station high-tension power lines, suspended from steel pylons, march across the landscape linking these remote generating locations to the national grid.

Most nuclear installations were fairly remote and when they were developed in the late 1940s or early 1950s car ownership and the mobility of the workforce was generally fairly low, especially amongst the general production staff. An essential component any facility was accommodation to house the workforce. Research staff might be housed adjacent to the establishment, while at the power stations staff were generally housed way from the site. Purpose built estates were usually added to existing settlements as at Seascale, Cumbria, to serve the Sellafield complex, and Southminster, Essex, which was enlarged to house the workers from Bradwell-on-Sea.

Closer to the new power stations roads were also created or improved, firstly for construction traffic and in some instances for the movement of fuel canisters. Elsewhere, the power stations also ensured the survival of a number of railway branch lines that might otherwise have been closed during the 1960s. One example of which is the branch line to Southminster that was regularly used for the movement of fuel rod canisters and which saw an increase in passenger numbers after the construction of Bradwell power station.

The creation of nuclear research establishments also had the effect of attracting other high tech industries to their surrounding areas and creating pools of qualified workers for such industries. On closure and after decommissioning former nuclear sites such as Harwell and Winfrith are being developed as new centres of scientific excellence, based on the intellectual and local infrastructure legacy of the nuclear industry.

5 ARCHITECTURE

The architecture of the nuclear power stations is explicitly modern, reflecting the vision of the industry that it was at the vanguard of a new industrial revolution the 'Atomic Age', with 'the prospect of a source of illimitable power' (*Nuclear Engineering*, 1956, 1). Immediately after the Second World War the Ministry of Power and Fuel embarked on a massive programme of power station construction. The enormous generating capacity of many of these new stations, such as Sir Giles Gilbert Scott's 1947 Bankside (now Tate Modern) and Staythorpe, Nottinghamshire, by Cecil Howitt and Partners, was matched by their equally monumental brick exteriors (Figure 16). The Beaver Committee of 1953, which investigated the economy and construction of power stations, recommended that the use of brick in power station design should generally cease, although it might be permitted where it was clearly a cladding. This decision was partly made on aesthetic grounds, but as relevant to early 1950s Britain was the vast consumption of resources the construction of these stations represented, both in brick and steel and in man hours. It was estimated that Bankside power station alone was constructed from 4.2 million bricks.

Figure 16
London, Bankside power station, now Tate Modern
© English Heritage

In place of brick it urged that modern lightweight cladding materials such as asbestos and aluminium sheeting should be used. It also suggested that in place of insitu concrete work, more use should be made of prefabricated concrete panels (*Official Architecture and Planning* 1953, 589-90). The new power stations were all supported on steel and reinforced concrete frames, covered by pressed metal sheeting and lit by large glass windows (*see* for example Figure 9). Where brick was used it was mainly for infilling panels. Externally and internally, the use of colour was seen as an integral part of their design. The periodical *Nuclear Energy Engineer* predicting that the 'nuclear revolution will add a splash of brightness and cheerfulness to the industrial scene' (1958, 132). Some of the new nuclear power stations were the work of influential contemporary architects, such as, Sir Frederick Gibberd who designed Hinkley Point, Somerset, and Sizewell, Suffolk. Other well-known examples of his public commissions include the new Roman Catholic cathedral in Liverpool, the terminal building at London Heathrow airport and Harlow new town (Evans 1972, 169). Trawsfynydd, Gwynedd, was designed by Sir Basil Spence.

Gabrielle Hecht, in her study of the French nuclear industry (1998), argues that the nuclear power stations should also be seen as a 'technological spectacle'. As Alvin Weinberg , Director of the Oak Ridge National Laboratories, USA, commented in 1961, the monuments of Big Science will become the 'symbols of our time just as surely as she finds in Notre Dame a symbol of the Middle Ages' (Weinberg 1961, 161-4).

Collectively the architecture of the research establishments lacks the unity of the power stations. As a group their sites are a mixture of greenfield sites and locations that have been adapted from former uses. On the latter types of sites existing wartime buildings were often reused and some still remain in use today. Where new research establishments were built such as Winfrith, Dorset, great care was taken to ensure that they blended into the local landscape. Buildings were, for example, faced in buff and local dark Swanage brick and the asbestos surfaces were treated in two shades of grey/green. Care was also taken with the height of the structures and they were constructed on an intimate scale conducive to the work of a research community (Abbott 1958, 517-8, *Nuclear Energy Engineer* 1959, 438-9). Research establishments are also characterised by many one-off structures built to meet a particular scientific need.

Main components of a nuclear power station

Most nuclear power stations comprise a relatively small range of structures. Nevertheless, even with a group of power stations of the same type there is often considerable diversity in how structures are arranged. This was partly dictated by the local topography but also illustrates the slightly different technological options that were used at the various stations.

Reactor Building -

The reactor building is usually a multi-storey, steel-framed structure clad in metal sheeting with bands of horizontal glazing and ventilations panels; its principal function is to protect the reactor and its control system from the elements (*see* Figure 9). Alternatively, a handful of reactors are protected by domed structures such as the experimental AGRs at Sellafiled and Dounreay and the PWR at Sizewell. Reactor buildings have considerate foundations to support the weight of the reactor and a basement through which services are channelled. Entry into this building is strictly monitored and anyone entering it is obliged to wear a film badge to record the any radiation they might be exposed to. Stairs and lifts give access to its different levels.

At the centre of the building is the reactor, its principal parts comprising the vertically arranged fuel elements, moderator, coolant and control rods are contained by shielding, which may be of welded steel, but is usually of reinforced concrete. During normal operations the reactor is concealed below a segmental floor, sections of which are removed during refuelling. To the sides of the reactor hall are the remotely controlled machines used for handling the fuel elements. Also within this building is the main reactor control room and other monitoring equipment on different levels. Spent Magnox fuel rods are intensely radioactive and are removed from cores by remote handling devices. They are also subject to residual heating and are normally passed down chutes to cooling pools before they are moved off-site for reprocessing. The cooling pools may be housed in a single building, but more usually each reactor has its own cooling pool.

Close to the reactor, but their position may vary according to a particular design, are the heat exchangers, in most British reactors carbon-dioxide is used as the coolant to remove heat from the reactor to the heat exchangers where it is converted to steam to power the turbines, which are used to produce electricity. Also associated with the reactor building are carbon dioxide storage vessels and the water treatment plant and pump house. Offshore water intake installtions may also be found.

Ferro-concrete cooling towers, more usually associated with conventional power stations are found at the two early Magnox stations at Calder Hall (Sellafield) and Chapelcross. Each station has four towers, one per reactor.

Turbine Hall

The turbine hall is normally a separate structure and similar in form to the reactor building it is normally steel-framed with metal cladding, although sections may be clad in brick. This building is dominated by the turbine hall, a large open space, with the turbo alternators at ground floor level with a raised steel deck walkway to give access to the turbines. On this steel deck are usually found a number of control and monitoring panels. Within this building are also found the main control room and small workshops where minor maintenance work is undertaken, stand-by diesel generators are also usually located in this structure. On the rear of the turbine hall are electrical transformer bays.

High tension cables link the turbine hall to a large electricity switching station, which is usually off site, which in turn connects to the national grid.

Ancillary buildings

Within a power station the ancillary buildings may be subdivided into two main groups, less specialised structures that might be found within any large industrial concern including administrative buildings and canteens, the other group are classified as active ancillary buildings. In the latter group there is a risk of radioactive contamination and precautions must be taken. Active ancillary buildings include buildings associated with fuel storage and handling, reactor maintenance, changing facilities and health physics.

Due to the hazardous nature of many of the materials handled by the industry, a distinctive feature of the industry is the range of elaborate safeguards taken to protect the workforce and the site. All the sites are surrounded by security fencing and access is tightly controlled usually through a single entry point. Internally the sites are zoned and movement between the zones controlled by further fences and gates, and again movement within buildings is tightly regulated and compartmentalised.

Special clothing may also be required certain sections of the plant and personal monitoring equipment in the form of individual dosimeters is a requirement for everyone entering restricted areas (Smart 1984, 24-5). In common with other industries where hazardous materials may be encountered there are changing areas for donning working or protective clothing and health monitoring facilities. Due to the slight risk of clothing being contaminated with radioactivity all sites are equipped with their own laundries.

Visitor facilities

Figure 17
Heysham, Lancashire, observation tower, its entrance was bricked up after the 2001 terrorist attacks on New York
© English Heritage

Secrecy, scientific complexity and a few well-publicised accidents have served to make some people fearful of the nuclear industry. Another aspect of regarding nuclear power stations as 'technological spectacles' is that they may be visited, viewed and toured as one might a historic monument or museum (Hecht 1998, 201-240). To both counter concerns about the industry and to celebrate the scientific achievement they represent the industry has been very keen to explain its operations to the local community and others through purpose-built visitor centres (Figure 18 & 19). These are usually located outside of a site's secure perimeter and may be situated in modest yet striking structures,

Figure 18
Trawsfynydd, Gwynedd, the visitor centre is to the left overlooking the lake, the reactor buildings were designed by Sir Basil Spence
© English Heritage

Figure 19
Heysham, Lancashire, the visitor centre
© English Heritage

such as the Sellafield visitor centre. At Heysham, Lancashire, an observation tower was provided overlooking the power station and the vast work camp created for its construction (Figure 17). Part of this camp is now covered by a nature reserve symbolising that nuclear power stations and nature may live together in close harmony (Figure 20).

Figure 20
Heysham, Lancashire, the power station viewed from the nature reserve
© English Heritage

Since September 2001, concerns about possible terrorist attacks, coupled with the decommissioning of many power stations, have led to the closure of most visitor centres and the cessation of public tours.

6 Nuclear Power a technical summary

In common with conventionally fired power stations nuclear power stations generate electricity using steam turbines coupled to electricity generators. The essential difference between the two is that conventional power stations produce heat energy by chemical methods, by the burning of coal, gas, oil or other materials, whereas in a nuclear power station a continuous output of intense heat is generated by continuously splitting the nuclei of atoms – either of uranium or plutonium.

Some basic physics

An atom is made up of protons, neutrons and electrons (*see* Figure 21). The proton has a positive electrical charge, the electron a negative charge and as its name suggests the neutron is neutral. Protons and neutrons form the core of nucleus of an atom around which the electrons rotate in various orbits. Together neutrons and protons are known as nucleons, the neutrons having the effect of aiding the positively charged protons to bind together. Normally an atom will have an equal number of protons and electrons, making it electrically neutral. The mass of an atom is calculated by adding the number of protons and neutrons together, thus helium (Figure 21) has a mass of 4. The atomic number of an element is defined by the number of its protons; hence helium has an atomic number of 2. Most species of atoms may be characterised by their atomic and mass number, or by their name and mass number, this is referred to as a nuclide. Helium-4 is a nuclide comprising 2 protons and 2 neutrons. In a stable nucleus the number of protons and neutrons will be roughly equal. In an unstable nucleus, with an excess of neutrons, they tend to transform themselves to a more stable form by the emission of a negatively charged electron, a beta particle, thereby converting a neutron into a proton. Where there is an excess of protons, by losing positive charge by the emission of a positron they are converted into a neutron. Any excess energy left in the nucleus is lost through the emission of gamma rays, discrete quantities of energy without mass or charge. These processes are known as radioactivity (NRPB 1989, 7).

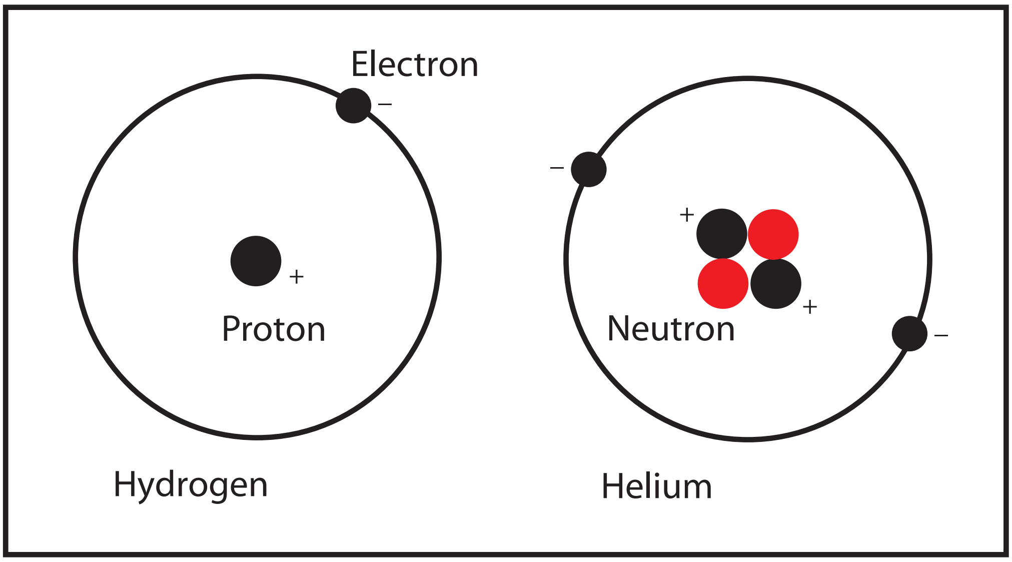

Figure 21
Atomic structure

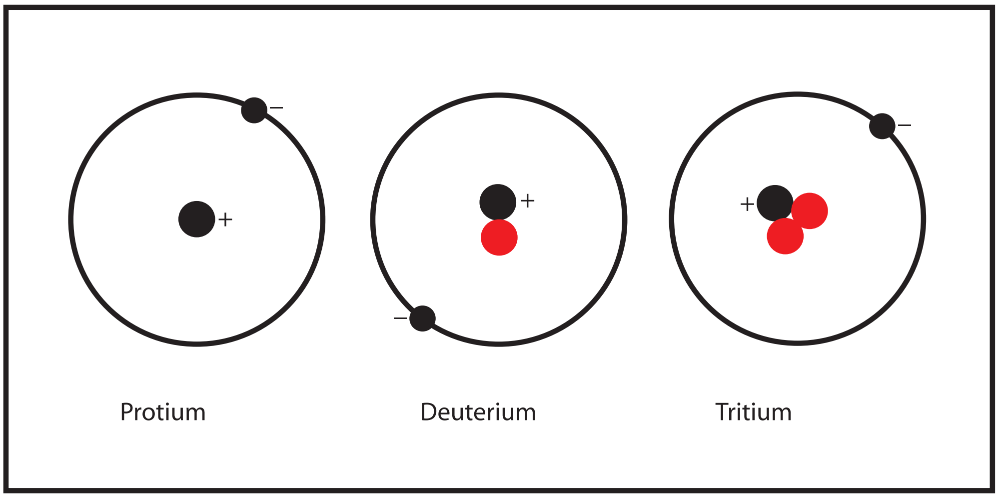

Figure 22
Nuclear isotopes

In any given chemical element the number of protons in the nucleus is constant, but the number of neutrons may vary resulting in a different mass. An element may therefore have several types of atoms (*see* Figure 22), these are known as isotopes, some occur naturally, while others are artificially created in a reactor by bombarding atoms with neutrons. Isotopes are numbers and are referred to by the number of the nucleons, uranium-238, for example, contains 92 protons and 146 neutrons.

The principles of nuclear power

Nuclear reactors generate heat that is then converted into steam to power turbines, which in turn generate electricity. The heat is produced by the continuous splitting of atoms, a process known as 'fission' (*see* Figure 23). Some types of heavy nuclei, in particular uranium and thorium, experience spontaneous fission; others may be made to fission by the addition of energy, for example by neutron bombardment. The only material that is naturally fissile to a significant extent is uranium 235, which comprises just 0.7% of natural uranium.

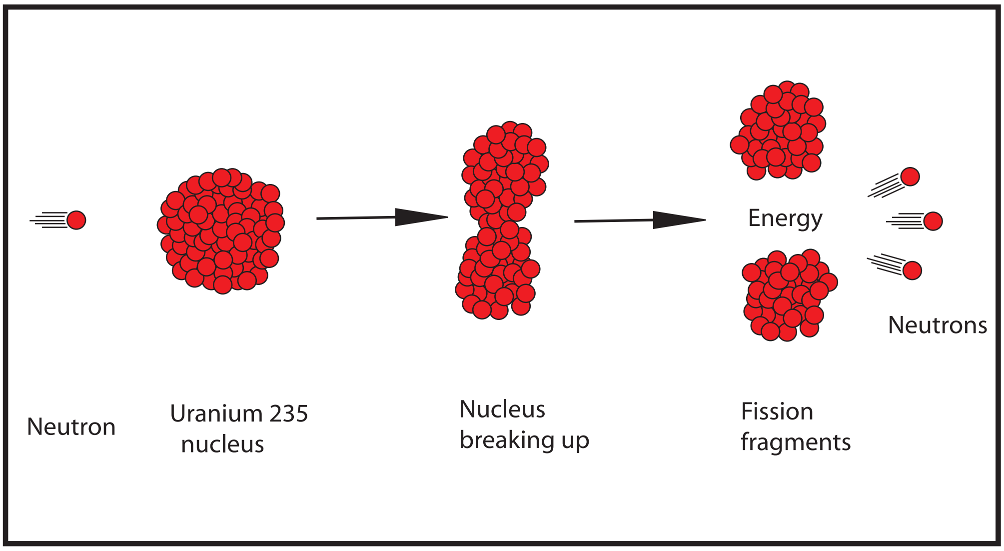

Figure 23
Nuclear fission

During the fission process energy is released, mainly in the form of kinetic energy (the energy of motion) of the fission fragments. This is rapidly converted to thermal energy, which causes the temperature of the fuel to rise, this heat may then be extracted by a coolant and through a heat transfer system may be used to generate stream.

During the fission process the unstable fission fragments give off neutrons. These may be split into two types, prompt neutrons, which are produced almost instantaneously and delayed neutrons that might be emitted seconds or minutes later. The emission of neutrons has a number of consequences; firstly, it allows a nuclear chain reaction to be sustained. Secondly, it results in the creation of transuranic elements (those with an atomic number greater than uranium), produced by in non-fission reactions by the absorption of neutrons by the uranium fuel. It is by this method and beta decay that plutonium is produced as a by-product of power generation. Neutron absorption by uranium-238 produces uranium-239, which through beta decay produces neptunium-239 and then plutonium-239. Thirdly, neutrons cause the materials of the power plant to become radioactive (Martin and Harbison 1986, 131-2; 135-6).

As we have seen above, in a nuclear chain reaction fission results in the release of neutrons, some, however, will be absorbed in non-fission reactions and others will be lost to the system. To minimise the loss of neutrons the reactor core is constructed from materials that are less prone to absorbing neutrons and by lining the core with a reflector. A core also needs to reach a certain size, or critical mass, before a chain reaction may be sustained. If in a reaction 2.3 neutrons are released and 1.3 are reabsorbed, 1 neutron remains to sustain a constant critical reaction. If the absorption rate was to rise to 1.31, then only 0.99 neutrons would be available for fission and the fission rate would decrease in this sub-critical reaction. Conversely if the absorption rate declined to 1.29, the fission rate would rise in super-critical reaction (Martin and Harbison, 1986, 133).

Reactor types

The choice of a particular reactor type may be seen as the result of the dynamic interplay of technological, political, economic and cultural factors. The chief engineering considerations in the design of the reactor are its fuel, moderator and coolant. The most commonly used fuels are uranium^{233}, uranium^{235} and plutonium, moderators may be of carbon (graphite), light hydrogen (ordinary water) and heavy hydrogen (heavy water) and for coolants water, heavy water, liquid metals and gases (such as carbon dioxide) are used (Radford 1961, 75).

To control the chain reaction a *moderator* is required to slow down the neutron bombardment and to regulate the amount of heat produced. Control rods made of boron or silver may be inserted between the fuel elements in the reactor core to absorb neutrons and control the chain reaction (Buckley 2004, 4). The heat generated during fission is removed by the coolant either water or gas, this is then generally taken to heat exchangers where it is converted to steam to power the electricity generating turbines. In some types of reactors the water is allowed to boil in the core and the steam is passed directly through the turbines.

Reactors may be classified into two main types, thermal reactors and fast reactors. In a reactor the chain reaction, or fission, is maintained by the collision of neutrons with the uranium fuel. Neutrons generated by fission are referred to as ‘fast’ neutrons once they have been slowed down by the moderator they are known as ‘thermal’ neutrons. To make the collisions more likely the neutrons are slowed down, or thermalised, by a moderator, either graphite or water. Thermal reactors may therefore be divided into two broad groups graphite moderated and water moderated. In a fast reactor there is no moderator.

The section below briefly describes the reactor types that are currently in use by the nuclear power industry or that have been used within research establishments. Some examples of common foreign reactor types are also included for comparison. The information below is taken from various sources, for a compact guide *see* AEE Winfrith 1977.

Thermal reactors

Graphite Moderated

Magnox

The Magnox fleet of 11 nuclear power stations, with a total of 26 reactors, is a technology unique to the United Kingdom and represents the first generation of British nuclear electricity generating reactors developed from military reactor technology. As a result of this ancestry the design has a low energy efficiency. They use natural uranium^{235} as fuel, which is encased in magnesium alloy, which gives its name to this group of stations (Figure 24). The core of a Magnox station is constructed from a graphite moderator; this is assembled from thousands of accurately machined graphite bricks. These are pierced by numerous vertical channels into which the fuel rods are inserted. Heat produced by the fuel rods is removed by pressurised carbon dioxide, which is pumped into the base of the pressure vessel containing the reactor and leaves through gas ports at its top. It then passes into a heat exchanger comprising many miles of water pipes before passing back into the reactor (Radford 1961, 76). In the early versions of this design the core is contained within a steel pressure vessel surrounded by a concrete shield with the steam generators located on

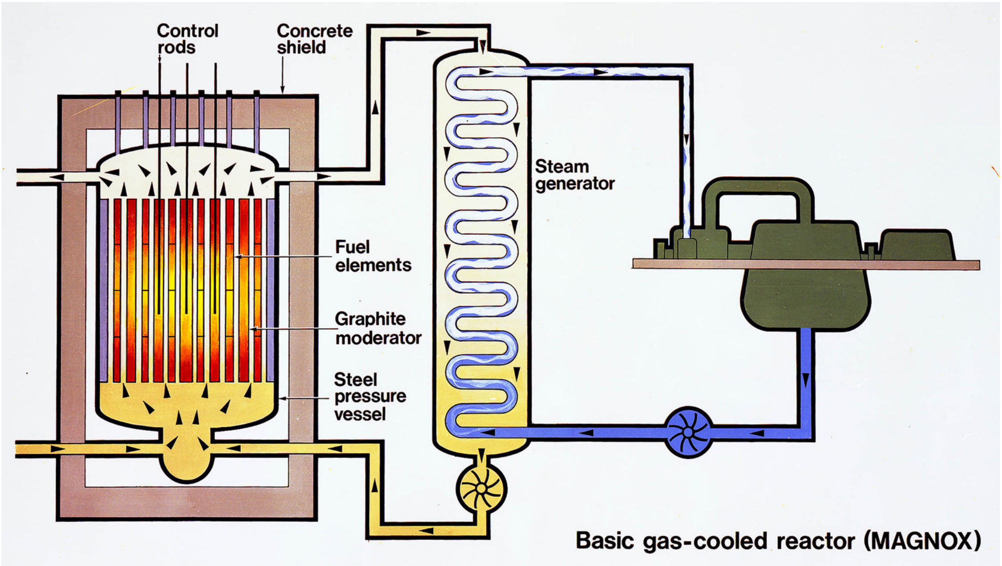

Figure 24
Diagrammatic cross-section through a Magnox reactor WH76-369-2 © UKAEA

the outside. In later designs there is a concrete pressure vessel with steam generators contained within it.

It is anticipated that all the Magnox plants will finish generating electricity by 2010, some may cease operation earlier if significant investment is needed to maintain plant safety or performance. The associated Thermal Oxide Reprocessing Plant (THORP) at Sellafield will probably cease operation in 2012 (DTI 2002, 48), *see* below.

Advanced Gas Cooled (AGR)

Gas-Cooled Reactors (GCRs) and Advanced Gas-Cooled reactors (AGRs), were the second generation of commercial reactors and represent an advance on the Magnox design, as with the Magnox fleet are a reactor design unique to the United Kingdom (Figure 25). In common with the Magnox stations they use pressurised carbon dioxide as the coolant and graphite as the moderator. The main differences are that the coolant is held at a greater pressure than in the Magnox stations and it has a far higher outlet temperature

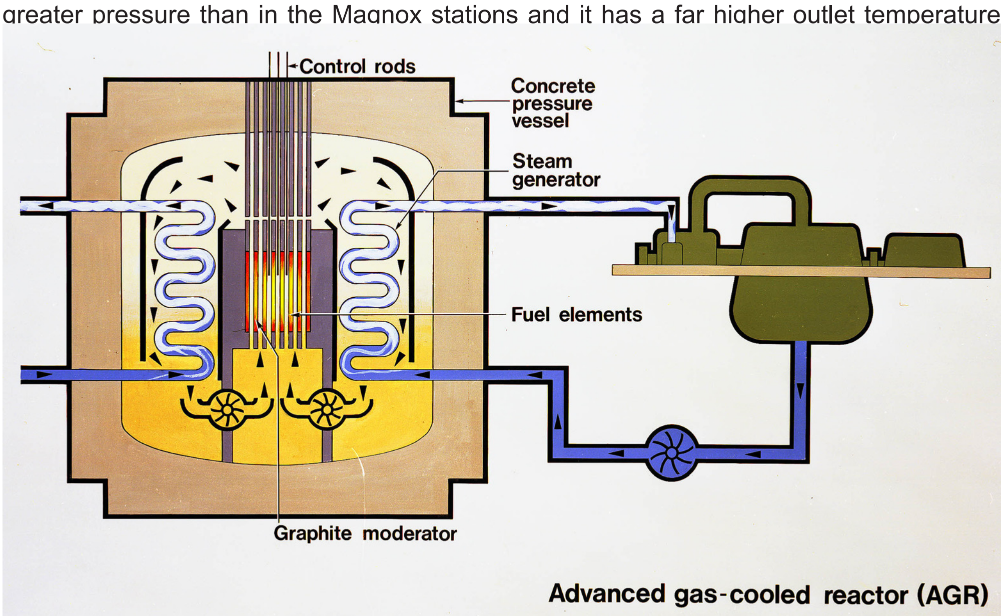

Figure 25
Diagrammatic cross-section through an Advanced Gas Cooled Reactor
WH76-369-2
© UKAEA

as it leaves the reactor. In place of natural uranium their fuel is slightly enriched uranium pellets encased in stainless steel tubes, which are manufactured at BNFL Springfields and reprocessed in the THORP facility at BNFL Sellafield. The reactor and steam generators are housed within a concrete pressure vessel. Some of the advantages of this system are that it is able to operate at higher temperatures and produce more power therefore allowing for a more compact plant design to be used. Since 1963, 15 AGRs have been built and operated in the United Kingdom, two power stations of this type will remain in operation until at least 2023.

High Temperature Thermal Reactor

This type of reactor uses uranium dioxide fuel coated in silicon carbide, bonded into a graphite matrix and assembled with graphite into a fuel element. The advantage of this system is that fuel may operate at a higher temperature, one consequence of this is that if carbon dioxide was used as the coolant it would corrode the graphite. To overcome this helium is used as the coolant. The heated helium is then used to produce steam to drive a turbine which in turn generates electricity. This type of reactor has only been used for experimental purposes in the United Kingdom.

Water Moderated

Pressurised Water Reactor (PWR)

The majority of the world's commercial reactors are Pressurised Water Reactors (PWR), and are based on a design originally developed in the early 1950s in the United States for submarine propulsion. One of the advantages of the PWRs is that because water is a more effective moderator than graphite it results in a more compact plant design. They may also be referred to as Light Water Reactors (LWR), to distinguish them from reactors that use heavy water as the coolant, as in the Canadian CANDU plants (*see* below).

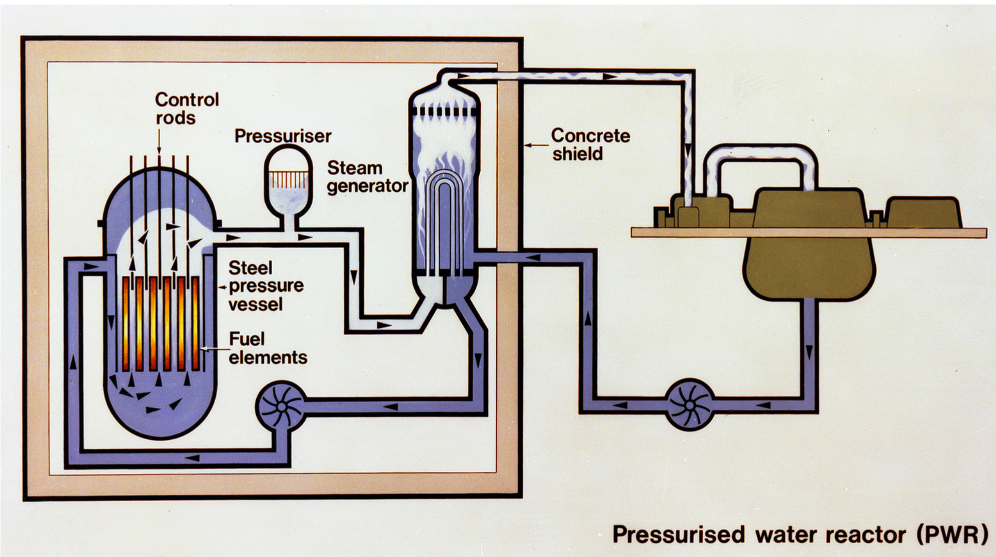

Figure 26 *Diagrammatic section through a Pressurised Water Reactor WH76-369-8 © UKAEA*

In this system water is pumped at high pressure through a pressure vessel where it acts as both moderator and coolant. The fuel is enriched uranium dioxide contained with Zircaloy (zirconium alloy) tubes. As the water is under pressure it does not boil and is used to heat water in a secondary circuit in a steam generator to produce steam to turn the station's turbines. The reactor is contained within a concrete biological shield, which is contained within a secondary containment shield.

Figure 27 *Sizewell, Suffolk, to the right is the 1960s Magnox station Sizewell A and to the left the is the 1200 MWE Pressurised Water Reactor © English Heritage NMR 23495/12*

One pressurised water reactor is in operation in the United Kingdom at Sizewell B, Suffolk (Figure 27).

Boiling Water Reactor (BWR)

A related system is the Boiling Water Reactor (BWR), which is effectively a PWR without the steam generator. In this type of reactor water is pumped through the core at a lower pressure than in a PWR, the water again acting as both moderator and coolant. It also uses enriched uranium dioxide encased in Zircaloy as fuel. About 10% of the water is converted to steam and passed through the turbines to generate electricity. Although this is a simpler system, lacking a steam generator, a major disadvantage of its operation is that contaminated steam is spread throughout the plant.

Steam Generating Heavy Water Reactor (SGHWR)

In this reactor uranium dioxide fuel is held in Zircaloy cans, the fuel elements are formed into clusters in separate pressure tubes which are in turn held in a tank of heavy water, which acts as the moderator. Ordinary water (light water) at pressure is passed over the fuel in the pressure tubes and the resulting steam is used to drive a turbine coupled to a generator. This type of reactor has only been operated for experimental purposes in the United Kingdom.

Pressurised Heavy Water Reactor (CANDU)

CANDU is a Canadian designed reactor, the acronym being derived from CANadian DeUterium oxide (heavy water), the latter being used for the moderator and coolant. The heavy water is pumped through the Zircaloy fuel tubes, containing natural uranium oxide, to a steam generator where it boils light water the resulting steam is piped to the turbines. This design does not require the pressure vessel of the PWR type reactors as the pressure tubes provide the containment. No reactors of this type operate in the United Kingdom.

Boiling Water, Graphite Moderator Reactor

This type of reactor is only found in countries of the former Soviet Union. These reactors use uranium dioxide fuel enriched to about 2 percent and held in Zircaloy pressure tubes in a graphite core. In operation water is pumped through the pressure tubes and the resulting steam is piped through the turbines. It is a complex design as the graphite, water and steam serve to moderate the neutrons in the core. It was a reactor of this type that exploded at Chernobyl in 1986 when the operators breached a number of safety procedures.

Homogeneous Reactor

A reactor where the fuel is suspended in a solution or suspension that could also operate as the coolant and moderator. In the United Kingdom, this type has only been used in research reactors.

Fast Reactors

During the 1950s, when there were concerns about the supply of uranium, fast breeder reactors were seen as the answer to the country's energy needs. For in this type of reactor more fissionable material is produced than the reactor consumes.

Fast breeder reactors use fuel that is highly enriched in fissile atoms, either with a high proportion of uranium-235 or plutonium-239, or a mixture of the two. No moderator is used in this type of reactor and the neutrons move around at very high speeds. To ensure that the neutrons do not leave the core, it is surrounded by a reflector to bounce them back into the core. Due to the absence of a moderator these reactors have the advantage of being more compact than other types. Within the core is also a blanket of uranium carbide, which absorbs neutrons from the fission process to produce plutonium, which after reprocessing may be used to manufacture more reactor fuel. Plutonium extracted from spent reactor rods may also be used to produce fuel for fast breeder reactors. They may also be run to burn up plutonium. Heat from the core is extracted by liquid sodium which is continuously pumped through the core is used to heat sodium in a secondary circuit, which is in turn passed through a stream generator. This steam is then used to drive the turbines coupled to an electric generator.

British research into fast breeder reactors was centred at Dounreay in Caithness, but was halted in 1994. Current research into the development of this type of reactor is now mainly concentrated in France, Japan and Russia.

Nuclear fuel manufacture

In the United Kingdom, the manufacture and reprocessing of nuclear fuel has been the responsibility of British Nuclear Fuels Limited (BNFL) and its predecessors. As an initially state owned industry its factories were placed on sites already in government hands. At Capenhurst, Cheshire, a uranium enrichment plant was set up on the site of a wartime small arms ammunition factory and fuel elements are manufactured at Springfields, Salwick, near Preston, Lancashire, a former poison gas factory. Within the Sellafield complex Mixed Oxide (MOX) fuel is manufactured, it is also here where the reprocessing of spent fuel elements is undertaken.

The United Kingdom has no indigenous deposits of uranium ore and it is imported as ore concentrates from a variety of sources, including Canada, South Africa, Australia and United States. The concentrate is initially dissolved in nitric acid to give uranium nitrate from which uranium tetrafluoride is formed. In this form it may be processed to create different types of fuels for the differing reactor types.

In the plant at Capenhurst operated by Urenco enrichment may be carried out by two methods gaseous diffusion or by the gas centrifuge process. In the former uranium hexafluoride gas is pushed through a series of very fine filters that are able to separate the uranium-235 molecules from those of uranium-238, it is effectively a form of molecular sieving. Since each stage of the process only increases the concentration of uranium-235 by a very small amount the process is repeated many hundreds of time. The diffusion method operated until 1982 when it was superseded by the gas centrifuge process. This process was brought into operation at Capenhurst in 1977 and was one of the world's first industrial scale gas centrifuge plants. In this process uranium hexafluoride gas is spun at very high speed in rapidly rotating centrifuges. This has the effect of concentrating the heavier uranium-238 molecules towards the wall of the centrifuge and the lighter uranium-

235 molecules at its centre. The gas flow is arranged so that the uranium-235 rich gas at the centre of the centrifuge is directed to next centrifuge in the process, while the gas with a higher concentration of uranium-238 rich is drawn in the opposite direction.

From Capenhurst the uranium hexafluoride is taken to Springfields, Lancashire, (which is managed by the Westinghouse Group) where it is converted into uranium oxide. Here the uranium hexafluoride is reacted with steam to form uranyl fluoride and then reduced with steam and hydrogen to form uranium dioxide, which in powder form is used to manufacture the fuel pellets. At Springfields, the nuclear fuel is also canned, or placed in a container. The container enables the fuel to be safely moved in and out of the reactor; it securely locates the fuel within the reactor and protects the fuel from the coolant. It also acts as a container for the radioactive fission products that accumulate while it is in the reactor.

A variety of fuels are manufactured at Springfields for the different types of reactors. For the Magnox stations the uranium tetrafluoride is converted into metal form by the addition of magnesium, the uranium flows to the bottom of the furnace, which after cooling is re-melted and cast into rods. The rods are then machined to the correct dimensions and placed into the magnesium alloy fuel cans. One of the useful properties of this alloy is that it has a low neutron absorption rate, an important factor when using natural uranium as fuel (Nuttall 2005, 88-9). Fuel for Advanced Gas Reactors is made from uranium dioxide powder this is formed into pellets and stacked inside stainless steel tubes or fuel pins. In each tube are 64 pellets, 36 tubes are then grouped together inside a graphite sleeve to form a fuel assembly, a fuel technology unique to the United Kingdom. The Pressurised Water Reactor at Sizewell also uses enriched uranium fuel pellets, these are placed in zirconium alloy tubes about 3m in length, 264 of which are grouped together to create a fuel assembly (BNFL 2003).

In addition Springfields also manufactures a variety of intermediate products for export, these include uranium hexafluoride, enriched uranium dioxide powder, granules and pellets (BNFL 2003). Fuel production is due to cease at Springfields in the 2020s and by the following decade the site is projected to have been cleared (NDA 2005, 102).

Mixed Oxide fuel is manufactured at Sellafield, this comprises about 95 per cent uranium and 5 per cent plutonium. The uranium and plutonium may both be recovered from the reprocessing of fuel rods, this process may therefore be seen as part of the reprocessing part of the fuel cycle. In a process developed by BNFL plutonium dioxide is mixed with uranium dioxide, ground, and then tumbled to form granules. The granules are then feed into presses to form pellets, which are in turn transferred to boats and placed in a sintering furnace to harden them. They are then ground to a precise size, they then may be stored or loaded into fuel rods, which are then combined to create fuel assemblies. MOX is used in over 30 European reactors, but no reactors in the United Kingdom are licensed to use this fuel.

Reprocessing

At the end of their productive lives spent fuel rods may be reprocessed, this separates out 96 per cent uranium, 1 per cent plutonium and 3 per cent waste (Figure 28). There are two plants at Sellafield that undertake this work, B205, which reprocesses fuel from the Magnox fleet. The second is the Thermal Oxide Reprocessing Plant (THORP), that takes the spent fuel from the Advanced Gas Cooled Reactors (AGRs) and light water reactors, and is one of a handful of facilities of its type in the world (Norris *et al* 1994, 78).

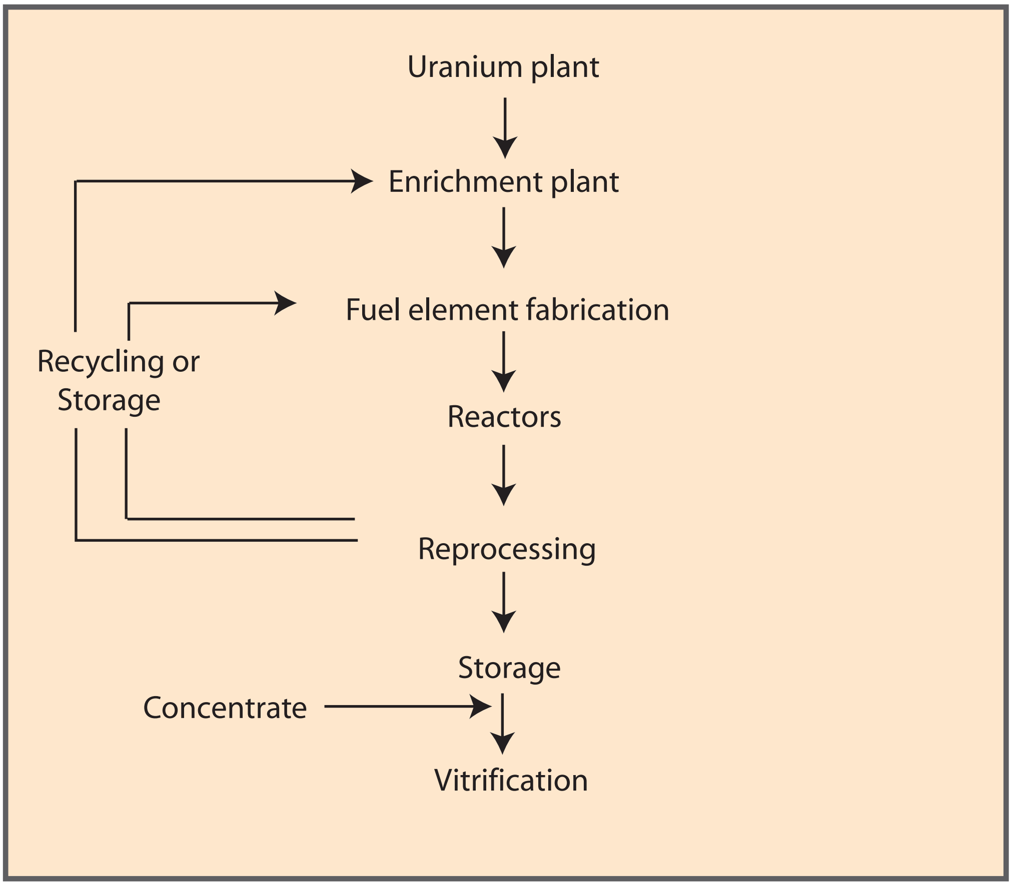

Figure 29
The nuclear fuel cycle

The Magnox fuel cycle is in part a legacy of the military origins of this programme where the reactors were designed to produce plutonium for weapons. The magnesium fuel containers were also thought to be unstable in damp air and after the removal from the reactor were generally stored underwater for short periods of time. It was also thought that the recovered plutonium would form the fuel for a series of fast breeder reactors. In contrast, fuel from the later series of reactors, the AGRs and the Sizewell Pressurised Water Reactor, may be stored indefinitely or disposed of. However, with the rising cost of uranium during the 1970s it was proposed to construct THORP. Work began on the plant in the late 1970s and by 1994 the £2.8 billion facility was in operation. The original economic arguments for this plant have, however, been undermined by the relative stability of uranium prices and therefore the very small market for the resulting MOX fuel. Additionally with the cancellation of the British fast breeder reactor programme in 1994, this removed the potential market for any reclaimed civil plutonium (Nuttall 2005, 89, 100). There is therefore little financial incentive to continue reprocessing and THORP, a leak at the plant in April 2005 has closed the facility for the foreseeable future (Brown 2005b, 13).

In the plant the fuel cans are mechanically stripped from the fuel, chopped into pieces and dissolved in hot nitric acid, which leaves only the container behind. The dissolved fuel and acid are then spun in a centrifuge to remove any remaining solids. In a series of columns using compressed air the mixture is separated into plutonium, uranium and radioactive wastes. The uranium solution is then concentrated by evaporation to form a powder, as is the plutonium. The two powders may then be stored separately or mixed together to form MOX fuel.

Initially fission product waste was stored in liquid form in large stainless steel tanks, equipped with compressed air agitators and elaborate pipework cooling coils. The preferred storage option is to convert this waste into solid glassy form by vitrification. This process takes place in the Sellafield Vitrification Plant, based on French processes it came into operation in 1990. In this process the liquid waste is mixed with silica and borax and then heated in a furnace to form a glass. This is then cast into cylindrical steel containers, in this chemically inert and practically insoluble form. These containers are stored in a specially designed building, where they are held in stainless tubes and cooled by natural air convection (King 1990, 67-8).

Depleted uranium

Another product of reprocessing is depleted uranium. It is a very heavy, dense and hard metal; these and other properties make it very attractive for a number of military applications, including in armour plating systems, penetration heads on bombs and missiles, and in the manufacture of anti-tank shells. It is also used as balance weights in some types of aircraft and yachts. Another advantage this metal has over comparable metals, such as tungsten, is that as a waste product of fuel rod reprocessing it is relatively cheap. It has a number of distinctive characteristics and requires specialised facilities for its handling and to ensure the safety of the workers during manufacturing. In England, a single factory for the manufacture of depleted uranium shells was set up in 1984 by Royal Ordnance Speciality Metals in a rehabilitated wartime building at Featherstone, Staffordshire (Figure

Figure 29
Featherstone, Staffordshire, Royal Ordnance Speciality Metals © English Heritage AA51029

Figure 30 *Featherstone, Staffordshire, Royal Ordnance Speciality Metals, one of the depleted uranium machining areas during decontamination operations © English Heritage AA05104*

29 & 30), production ceased in about 2003. In the production process depleted uranium was imported in powder form from the United States; then through various pressing and heating (sintering) processes it was rendered into solid billets for machining and finishing into anti-tank rounds.

Depleted uranium was also used in some nuclear weapons components which were manufactured by AWE Llanishen, Cardiff, this activity ceased in 1997 (Norris *et al* 1994, 73-6)

Waste

In 1955, when the civil nuclear power programme was first proposed it was stated that 'disposal of radioactive waste products should not present a major problem' (The Lord President of the Council 1955, 9). Today, around 80,000 cubic metres of radioactive waste is currently stored in the United Kingdom, a figure that will rise over the next decade as most of the country's nuclear power stations are decommissioned. The options for the long term disposal or storage of high, medium and low level wastes is currently being considered by the Committee on Radioactive Waste Management (CoRWM), which is due to report to the government in 2006. Some of the options being considered may require the construction of new buildings for long-term interim storage, where materials with relatively short half-lives might be stored prior to disposal. Similarly near-surface disposal in vaults or caverns may be also considered for short-lived wastes (CoRWM 2005, 21-2).

At present some very low level waste is buried on landfill sites and some low level waste is stored in specially engineered facilities on the site of a former Royal Ordnance explosives factory at Drigg, Cumbria. The future disposal of low activity waste is outside the remit of

CoRWM, but is being considered by a separate government review (CoRWM 2005, 5).

Another organisation involved in the management of radioactive waste is the Nuclear Industry Radioactive Waste Executive, United Kingdom Nirex Ltd was formed in 1982 and became a limited company in 1985 and achieved the status of an independent agency in April 2005. Its main function is to manage the long term disposal of Intermediate Level Waste. Geologically, around one third of the United Kingdom is thought to be suitable for the deep disposal of nuclear waste. During the 1980s NIREX undertook an assessment of around 500 sites, by 1989 a shortlist of 12 sites had been identified, this remained secret until May 2005 when it was disclosed under the Freedom of Information Act (Brown 2005a, 6; Morris 2005, 9).

7 Sources

Given the relatively small size of the nuclear industry its significance and controversial nature is reflected by a vast literature on its technology and politics. A search of the Cambridge University Library catalogue on the keywords 'atomic' and 'nuclear' revealed over 1300 books and over 90 journals. Some of the most important publications for the history of the United Kingdom's nuclear industry are by Margaret Gowing, former official historian to UKAEA. Unfortunately these only cover the early years of the industry, although later volumes are believed to exist in manuscript form. Many other related books and journals on applied physics, architecture, engineering and planning contain relevant information. In addition Parliamentary debates, recorded in *Hansard*, contain further material on the politics of the nuclear industry. Local repositories also hold a variety of archives relating to nuclear installations, including newspaper cuttings, photographs, videos, oral history interviews and official reports.

The main repository for primary documents detailing national nuclear policy is deposited in the National Archives, Kew; it also holds some technical reports produced by government research establishments. A useful guide to nuclear history files in the National Archives is available on the King's College web site www.kcl.ac.uk/lhcma although some of the information is now out of date.

Most technical drawings, manuals and photographs of individual sites are held by their operators, either centrally or on specific sites. One of the most important archives is that of the United Kingdom Atomic Energy Authority (UKAEA) which is held to National Archives' standards at Harwell, Oxfordshire, it encompasses both that site's activities and that of other UKAEA locations. The Atomic Weapons Establishment (AWE) maintains its own archives, which include detailed information on the infrastructure of its sites; much of this information remains classified. The library and archives of the Institution of Electrical Engineers, Savoy Place, London, holds extensive collections on the history of electricity supply including the nuclear industry.

English Heritage's National Monuments Record, Swindon, has relatively little material on the nuclear industry. Items include a handful of former Property Services Agency images of Burghfield and Sellafield, and images of power stations within the general vertical air photograph collection and some modern oblique air photography. The Royal Commission on the Ancient and Historical Monuments of Scotland (RCAHMS) holds an extensive archive of material donated to it by South of Scotland Electricity Board (now part of Scottish Power). This collection includes a number of photograph albums of the construction of Hunterston, North Ayrshire, 1960-75. RCAHMS's collections also contain air photographs of Dounreay, Highland; Torness, East Lothian, and Chapelcross, Dumfries and Galloway.

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www.british-energy.com British Energy

www.hanford.gov/doe/history US Department of Energy Hanford site

www.hse.gov.uk Health and Safety Executive

www.kcl.ac.uk/lhcma King's College London

www.subbrit.org.uk Subterranea Britannica

www.ukaea.org.uk United Kingdom Atomic Energy Authority

9 Acknowledgements

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10 Chronology

1895	December	Wilhelm Roentgen recognises x-rays
1896		Henri Becquerel discovers radioactivity
1897		Joseph John Thomson, professor of physics at the Cavendish Laboratory Cambridge discovers the 'electron'
1898 radium	December	Pierre and Marie Curie announced that they had separated from pitchblende.
1905		Albert Einstein published his theory of special relativity
1911		Ernest Rutherford discovers the nucleus
1913		Rutherford-Bohr model of the atom
1932 discovers	February	James Chadwick at the Cavendish Laboratory, Cambridge, the neutron
	14 April	John Cockcroft and Ernest Walton under Rutherford split the atom in the Cavendish Laboratory.
1938		German scientists Otto Hahn and Fritz Strassmann demonstrate nuclear fission
1940		Frisch-Peierls memorandum alerts the British government to the possibility of creating an atomic bomb
April		British MAUD Committee formed under chairmanship of George P Thomson to consider if it might be possible to construct an atomic bomb during the present war.
1941	July	Maud Committee report concludes that a nuclear weapon was feasible
	September	Winston Churchill decides to proceed with the development of an atomic bomb
October		Tube Alloys division formed within Imperial Chemical Industries as a cover for the British atomic work
1942	September	General Leslie Groves is appointed as the head of the United States atomic bomb project, the Manhattan Project, at Los Alamos, New Mexico
	December	First fission reactor started up by Enrico Fermi and his team in

		Chicago
1943		Quebec Agreement with United States
1945	16 July	The Trinity Test, First atomic bomb tested at Alamogordo, Mexico
	6 August	Atomic bomb dropped on Hiroshima
	9 August	Atomic bomb dropped on Nagasaki
	October	Atomic Research Establishment set up at former RAF Harwell, Oxfordshire, under John Cockcroft
1946		UK Atomic Energy Act passed
	24 January	United Nations Atomic Energy Commission established
	February	Production Division established at Risley, Cheshire, under Christopher Hinton
	June	UKAEA Harwell, construction of BEPO begins
	30 July	US Atomic Energy Act 'The McMahon Act' established the Atomic Energy Commission – it also forbade all exchange of information on atomic weapons, fissile material and nuclear power generation
1947	8 January	A small British cabinet committee decides to proceed with a British atomic bomb
		High Explosives Research' division established at Fort Halstead, Kent
	September	Work begins on the Windscale piles
1948	1 April	The British electricity industry was nationalised
	3 July	UKAEA Harwell, BEPO went critical
1950	October	Windscale first pile went critical
		Former RAF Aldermaston is acquired as the centre of the British atomic bomb project
1951	June	Windscale second pile went critical
1952	28 March	First piece of plutonium created ready for a British atomic bomb

	3 October	First British atomic bomb exploded at Monte Bello, NW Australia
1953	August	Work begins on two dual purpose PIPPA reactors at Sellafield to produce plutonium and electricity
	8 December	US President Eisenhower makes his ‘Atoms for Peace’ speech to the United Nations
1954		Atomic Energy Authority Act, United Kingdom Atomic Energy Authority formed
	June	Decision taken to build 2 more PIPPAS at Sellafield and 4 at Chapelcross, Dumfriesshire
	27 June	Soviet 5 megawatt research reactor at Obinisk begins generating electricity
	July	Decision taken to proceed with the development of the H-bomb
		First United States nuclear-propelled submarine *Nautilus* was launched, powered by a pressurised water reactor
1955	February	White paper announces intention to build 12 nuclear power stations between 1955 and 1965
	March	Construction of Dounreay fast reactor begins
1956	17 October	The Queen opens the Calder Hall power station
		Contracts placed for Magnox stations at Berkeley and Bradwell
1957		International Atomic Energy Commission established by the United Nations
	7 October	Fire in Pile No.1 at Windscale
	October	Construction of UKAEA experimental Advanced Gas Cooled Reactor begins at Windscale
1958		UKAEA Winfrith established for reactor development
1959	February	Chapelcross reactors opened
		Dounreay fast breeder reactor operational
		Atomic Energy Authority Act broadens areas of operation for UKAEA

1960		UKAEA Culham established for fusion research
1962	December	Windscale Advanced Gas Cooled Reactor commissioned
1963	February	Windscale Advanced Gas Cooled Reactor begins to supply electricity to the national grid
1964		Government announces the second phase of the civil nuclear power programme using Advanced Gas Cooled reactors.
1965		First Advanced Gas Cooled reactor chosen for Dungeness B
1971		Atomic Energy Authority Act establishes British Nuclear Fuels Limited and The Radiochemical Centre Ltd
1979	28 March	Three Mile Island, Pennsylvania, accident
		Advanced Gas Cooled reactors authorised at Heysham 2 and Torness
1986	26 April	Accident at the Chernobyl, Ukraine, Reactor Unit No.4 V I Lenin Nuclear Power Plant
1987	1 September	Atomic Weapons Establishment (AWE) formed from
		Atomic Weapons Research Establishment and Directorate of Atomic Weapons Factories
1989		British electricity generation industry privatised, except for nuclear power stations
1995		Sizewell B begins production
		Atomic Energy Act - UKAEA partially privatised
1996	July	Privatisation of the nuclear power industry
		Official opening of Sizewell B
1997		Kyoto Protocol on climate change
1998		Magnox shares transferred to BNFL
		Nuclear Electric renamed British Energy Generation Ltd, Scottish Nuclear becomes British Energy generation (UK) Ltd
1999		BNFL purchased Westinghouse, a United States company principally concerned with the construction of nuclear installations

2004	Energy Act established the Nuclear Decommissioning Authority
2005 1 April	Nuclear Decommissioning Authority fully operational
	BNFL announces it is to sell its Westinghouse division

11 Glossary

AEA	Atomic Energy Authority
AGR	Advanced Gas-Cooled Reactor – The fuel is slightly enriched uranium oxide clad in stainless steel. The coolant is carbon dioxide and the moderator is graphite.
AERE	Atomic Energy Research Establishment (Harwell)
Alpha particle	A positively charged particle that is emitted from some radioactive nuclei, comprises two protons and two neutrons.
Atom	A unit of matter that cannot be broken down further by chemical methods, comprises a nucleus surrounded by electrons.
AWE	Atomic Weapons Establishment – is operated on behalf of the Ministry of Defence by a licensee company (AWE plc) and managed by AWE Management Ltd a Consortium comprising BNFL, Serco and Lockheed Martin.
AWRE	Atomic Weapons Research Establishment, became AWE in 1987
BE	British Energy Generation plc, incorporates Nuclear Electric Limited (NEL) and Scottish Nuclear Limited (SNL)
Beta particle	Electrons emitted form a radionuclide during beta decay
BNFL	British Nuclear Fuels plc
BNG	British Nuclear Group, specialist clean-up arm of BNFL set up in 2004
Cladding	Protective coating around the reactor fuel
Control rods	A usually steel rod containing good neutron absorbers, such as boron and cadmium, which may be inserted into a reactor to control its activity.
CoRWM	Committee on Radioactive Waste Management, appointed in 2003 by UK government and devolved administration is Scotland, Wales and Northern Ireland. Its main task is to review the options for managing UK radioactive wastes.
DTI	Department of Trade and Industry

Electron	A particle carrying one unit of negative electrical charge.
Euratom	European Atomic Energy Community (EAEC) or Euratom, established in 1957 to encourage progress in the field of nuclear energy. FBR Fast Breeder Reactor
Fission	Splitting of a nucleus into two approximately equal parts known as fission fragments.
HLW	High Level Waste, heat generating waste, primarily derived from reprocessing of spent nuclear fuel.
ILW	Intermediate Level Waste, mainly derived from reprocessing spent fuel, general operations and maintenance of nuclear plant.
Isotopes	Two atoms are said to be isotopes if they are the same chemical element but have different masses. Their nuclei will have the same number of protons but a different number of neutrons and therefore different atomic masses.
JET	Joint European Torus, Culham, Oxfordshire, used in fusion research, operated by UKAEA on behalf of Euratom.
LLW	Low Level Waste, lightly contaminated scrap, includes building materials, metals, clothing, laboratory equipment, etc.
LMA	Liabilities Management Authority – responsible to the government to ensure that the nuclear legacy of BNFL and UKAEA is safely, securely and cost effectively cleaned up. It will also oversee the decommissioning of the Magnox reactors. It has been renamed the Nuclear Decommissioning Authority (NDA).
LMU	Liabilities Management Unit – an interim body established by the DTI to strengthen its oversight of the nuclear legacy prior to the establishment of the LMA (now known as the NDA).
Magnox	Magnesium alloy clad uranium fuel rod used in UK gas cooled reactors. The name is also applied to the first generation British reactors that used this type of fuel rod, all due to have ceased operation by 2010.
Moderator	A moderator is used to slow down the neutron bombardment during fission to the required rate and used as a control mechanism to regulate the production of heat. A moderator is typically placed between fuel elements and reactor core

	to absorb neutrons and thus regulate chain reaction.
Mox	Mixed Oxide Fuel made up of around 95% uranium and 5% plutonium, used only by Sizewell B
NDA	Nuclear Decommissioning Authority – a statutory non-departmental public body.
NEL	Nuclear Electric Limited, part of British Energy
Neutrons	An electrically neutral subatomic particle, produced by splitting, or fissioning of certain atoms inside a nuclear reactor. Neutron radiation is very penetrating and water and concrete are therefore used as a protection against it.
NIREX	Nuclear Industry Radioactive Waste Executive, United Kingdom Nirex Ltd - formed in 1982 it was made a limited company in 1985and in April 2005 became an independent agency. Its function is to manage the long term disposal of Intermediate Level Waste.
NRPB	National Radiological Protection Board
NYCOMED	Nycomed Amersham plc, an amalgamation of Amersham International, Pharmacia Biotech and Nycomed ASA, previously licensed as Amersham International, producers of radioisotopes.
PIPPA	A type of gas cooled, graphite moderated reactor designed to produce weapons grade plutonium and electricity
PWR	Pressurised Water Reactor – a reactor whose primary coolant is maintained under such a pressure that no bulk boiling occurs. The reactor uses water as a moderator or as coolant.
Proton	Positively charged particle, forms part of nucleus
Reprocessing	This process involves removing the metal casing from around the fuel, which is then dissolved in hot, concentrated nitric acid. The uranium, plutonium and waste are then separated by various chemical processes.
RWMAC	Radioactive Waste Management Advisory Committee – temporarily suspended March 2004
SGHWR	Steam Generating Heavy Water Reactor
SNL	Scottish Nuclear Limited, part of British Energy

SMP	Sellafied MOX Plant – recyles plutonium separated during reprocessing into MOX fuel for use in reactors.
THORP	Thermal Oxide Reprocessing Plant – located at Sellafield for the reprocessing of Magnox fuel rods by separating the uranium and plutonium from the waste.
UKAEA	United Kingdom Atomic Energy Authority
URENCO	Urenco (Capenhurst) Ltd, principally concerned with uranium enrichment

Appendix A List of Britain's Principal Nuclear Installations

	Site	Cnty		Easting	Northing	Main function	Notes
Atomic Weapons Establishment							
1	Aldermaston	BK	SU	595	636	Atomic Weapons Establishment	
2	Burghfield	BK	SU	68	68	Atomic Weapons Establishment	
3	Foulness	EX	TQ	987	917	Atomic Weapons Establishment	Range administered by QinetiQ
4	Orfordness	SF	TM	440	485	Atomic Weapons Establishment	owned by National Trust
British Energy Generation plc							
5	Dungeness B	KE	TR	O83	169	Advanced Gas Cooled Reactor	
6	Hartlepool	DU	NZ	530	270	Advanced Gas Cooled Reactor	
7	Heysham	LA	SD	412	595	Advanced Gas Cooled Reactor	
8	Hinkley Point B	SO	ST	212	460	Advanced Gas Cooled Reactor	
9	Sizewell B	SF	TM	473	635	Pressurised Water Reactor	
10	Hunterston B		NS	1835	5133	Advanced Gas Cooled Reactor	
11	Torness		NT	746	751	Advanced Gas Cooled Reactor	

British Nuclear Group Sellafield Ltd							
12	Capenhurst	CH	SJ	365	745	Fuel production and reprocessing	NDA Responsibility
13	Drigg	CU	SD	O55	990	Low level waste store	NDA Responsibility
14	Sellafield	CU	NY	O32	O35	Fuel production and reprocessing	NDA Responsibility
15	Calder Hall	CU	NY	O28	O38	Magnox	NDA Responsibility
Springfields Fuels Ltd							
16	Springfields	LA	SD	463	315	Fuel production and reprocessing	NDA Responsibility
Magnox Electric Ltd							
17	Berkeley	GC	ST	660	994	Magnox	NDA Responsibility
18	Bradwell	EX	TR	OO1	O89	Magnox	NDA Responsibility
19	Chapelcross		NY	2167	6970	Magnox	NDA Responsibility
20	Dungeness A	KE	TR	O83	169	Magnox	NDA Responsibility
21	Hinkley Point A	SO	ST	212	460	Magnox	NDA Responsibility
22	Hunterston A		NS	1835	5133	Magnox	NDA Responsibility
23	Oldbury	GC	ST	605	945	Magnox	NDA Responsibility

24	Sizewell A	SF	TM	473	635	Magnox	NDA Responsibility
25	Trawsfynydd		SH	691	381	Magnox	NDA Responsibility
26	Wylfa		SH	352	939	Magnox	NDA Responsibility
UKAEA							
27	Culham	OX	SU	535	955	UKAEA	NDA Responsibility
28	Dounreay		NC	98	67	UKAEA	NDA Responsibility
29	Harwell	OX	SU	475	865	UKAEA	NDA Responsibility
30	Risley	CH	SJ	657	923	UKAEA	
31	Winfrith	DO	SY	820	870	UKAEA	NDA Responsibility
32	Windscale	CU	NY	O28	O38	UKAEA	NDA Responsibility

Appendix B List of Britain's Nuclear Power Stations England

	Site		Reactor type	Operational	Status	Site Licence holder	
1	Berkeley	GC	Magnox	1962-1989	Decommissioning	Magnox Electric Ltd	2 reactors
2	Bradwell	EX	Magnox	1962-2002	Closed May 2002, Decommissioning	Magnox Electric Ltd	2 reactors
3	Calder Hall	CU	Magnox	1956-2003	Decommissioning	Brit Nuc Grp Sellafield	4 reactors
4	Dungeness A	KE	Magnox	1965	Operational, to close Dec 2006	Magnox Electric Ltd	2 reactors
	Dungeness B	KE	AGCR	1985-88	Operational	British Energy plc	2 reactors
5	Hartlepool	TE	AGCR	1984-5	Operational	British Energy plc	2 reactors
6	Heysham 1	LA	AGCR	1984-5	Operational	British Energy plc	2 reactors
	Heysham 2	LA	AGCR	1988-89	Operational	British Energy plc	2 reactors
7	Hinkley Point A	SO	Magnox	1965-2000	Decommissioning	Magnox Electric Ltd	2 reactors
	Hinkley Point B	SO	AGCR	1976-78	Operational	British Energy plc	2 reactors
8	Oldbury	GC	Magnox	1967	Operational, to close Dec 2008	Magnox Electric Ltd	2 reactors
9	Sizewell A	SF	Magnox	1966	Operational, to close Dec 2006	Magnox Electric Ltd	2 reactors
	Sizewell B	SF	PWR	1995	Operational	British Energy plc	1 reactor

List of Britain's Nuclear Power Stations Scotland and Wales

	Site		Reactor type	Operational	Status	Site licence holder	
Scotland							
10	Chapelcross		Magnox	1959-2004	Decommissioning	Magnox Electric Ltd	4 reactors
11	Dounreay		Fast Breeder	1976-?1994	Decommissioning	UKAEA	
12	Hunsterton A		Magnox	1964-1989	Decommissioning	Magnox Electric Ltd	2 reactors
13	Hunsterton B		AGCR	1976-77	Operational	British Energy plc	2 reactors
14	Torness		AGCR	1988-89	Operational	British Energy plc	2 reactors
Wales							
15	Trawfynydd		Magnox	1965-1991	Decommissioning	Magnox Electric Ltd	2 reactors
16	Wylfa		Magnox	1971	Operational, to close 2010	Magnox Electric Ltd	2 reactors

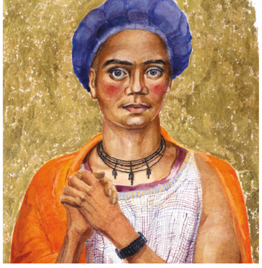
Appendix C List of research reactors in England

	Site		Name	Reactor type	Dates	Status	Notes
1	AWE Aldermaston	BK	HORACE	light water moderated	May-58	Decomm	R61.5 design for HERALD
			HERALD	light water moderated & cooled pool	09/58-09/88	Decomm	R61.1 General research
			MERLIN II	Swimming pool	195?		
			VERA		196?	Decomm	
			VIPER	Pulsed fast reactor	1967-	Active	Hardening experiments
2	AEI Aldermaston	BK	Merlin	Swimming pool, 4 position core, light water	1958	Decomm	Medium Energy Research
3	Derby, Raynesway	DR	Neptune	Zero power	196?	Active	Submarine propulsion
4	UKAEA Harwell	OX	GLEEP	Thermal	15/08/1947-90	Decomm	Europe's 1st nuclear reactor
			BEPO	Thermal, air cooled graphite moderator	05/07/1948-68	Decomm	Isotope production
			DIDO	Thermal (high flux) heavy water moderator	21/11/1956-90	Decomm	Materials testing
			DIMPLE	Thermal zero energy heavy water moderator	26-Jul-54	Decomm	Thermal reactor studies
			HAZEL	Homogeneous assembly zero energy	Feb-58	Decomm	formerly ZETR II
			LIDO	Swimming pool	Sep-56	Demolished	Marine propulsion

			NEPTUNE	light water cooled and moderated	07-Nov-57	Decomm	Marine zero energy reactor
			NERO	zero energy, graphite moderated	195?	Decomm	Research for AGR
			PLUTO	Thermal (high flux) heavy water moderator	25/10/1957-90	Decomm	Materials testing
			ZEPHYR	Fast thermal, zero energy fast reactors	Feb-55	Decomm	Fast reactor studies
			ZEUS	Fast thermal, zero energy fast reactors	22-Dec-55	Decomm	Dounreay design evaluation
			ZETA	Zero Energy Thermonuclear Assembly	12-Aug-57	Decomm	
5	UKAEA Winfrith	DO	DRAGON		1959	Decomm	AGR prototype
			ZENITH	High Temperature Zero Energy Reactor	1959	Decomm	
			SGHWR	Steam Generating Heavy Water Reactor	1968-90	Decomm	
6	Woolwich	LO	JASON			Removed	Royal Navy training
7	UKAEA Windscale	CU	W Piles	Graphite moderator, water cooled	1950-57	Decomm	
			HERO		1961	Decomm	
			AGR	Advanced gas cooled reactor	1961	Decomm	Prototype AGR
8	Risley	CH		Highly enriched uranium	1962-	Demolished	M/cr & Lvpl Universities
9	Billingham					Decomm	ICI research reactor
10	Newham	LO			1966-1982	Removed	Queen Mary College

List of research reactors in Scotland

	Site		Name	Reactor type	Dates	Status	notes
11	UKAEA Dounreay		DMTR	Thermal high flux heavy water	May-58	Decomm	D Materials Testing Reactor
			DFR	Dounreay Fast Reactor ?FRED	Nov-59	Decomm	Shut down 1977
			PFR	Prototype Fast Reactor	1974-1994	Decomm	
	Royal Navy		Vulcan		1965		Naval research reactor
						Decomm = Decommissioned	



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