FUNDAMENTALS OF NUCLEAR ENERGY

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Summary

A number of scientific discoveries regarding the nature of atoms and their characteristics were made over a relatively short period of time. These lead to the splitting of the atom and the realization that potentially large amounts of energy could be released in the fissioning of certain nuclides. Work on this was expedited in secret during the Second World War during which time the first nuclear reactors were built and the first atomic bombs exploded. Following the Second World War reactor development proceeded rapidly for the production of fissile plutonium and for the generation of electric power. As designs were refined, nuclear reactors tended to be built for specialized purposes such as for material research and isotope production, for propulsion of submarines and aircraft carriers and for electric power production. The discovery and development of nuclear radiation and energy was associated with well known historical figures many of whom won Nobel Prizes for their efforts. Over twenty Nobel Prizes were awarded in physics and chemistry for advancement in this field over a fifty year period indicating the significance of these achievements.

Nuclear energy has, over the years, proved economical in the large scale generation of electric power. Although capital costs are high, fuel costs are low. More recently, following serious accidents at Three Mile Island and Chernobyl, great emphasis has been put on ensuring safety in nuclear operations.

Nuclear reactors operate by the fissioning of fissile uranium which is induced by neutrons. Each fissioning process results in the splitting of the nucleus of an atom into two fission products and, on average, two or three free neutrons, one of which is utilized

to continue the process. The fission products fly apart with high kinetic energy, which is degraded into heat, which in turn is removed and used to generate power in a thermodynamic cycle. The neutrons diffuse through a moderator to reduce their energy and so increase their probability of causing fission in other uranium nuclei. Excess neutrons are absorbed by reactor materials, including adjustable control rods, so that a continuous chain reaction can be maintained to release a steady flow of heat, which is removed by the reactor coolant and used to generate steam, which in turn is used to drive a turbine-generator.

1. Historical Review

1.1. Historical Discoveries

Certain remarkable discoveries related to nuclear energy were made in a relatively short period of time. Only by 1920 was the basic structure of the atom understood while the existence of the neutron was confirmed in 1932. This was a pivotal discovery since the neutron is the key element in establishing a fission chain reaction. Just ten years later in 1942 the first self sustaining chain reaction was established and by 1956 the technology had advanced to the point where a nuclear fission reactor could produce electric power on a commercial scale.

Any historical review of this field needs to consider the connection between the discovery, the researcher and the recognition, as illustrated in Figure 1, as well as the timeline linking the discoveries and the lives of the researchers. Much literature is available covering each of the three aspects shown in Figure 1. This review provides a summary of each of these and their relationship with one another.

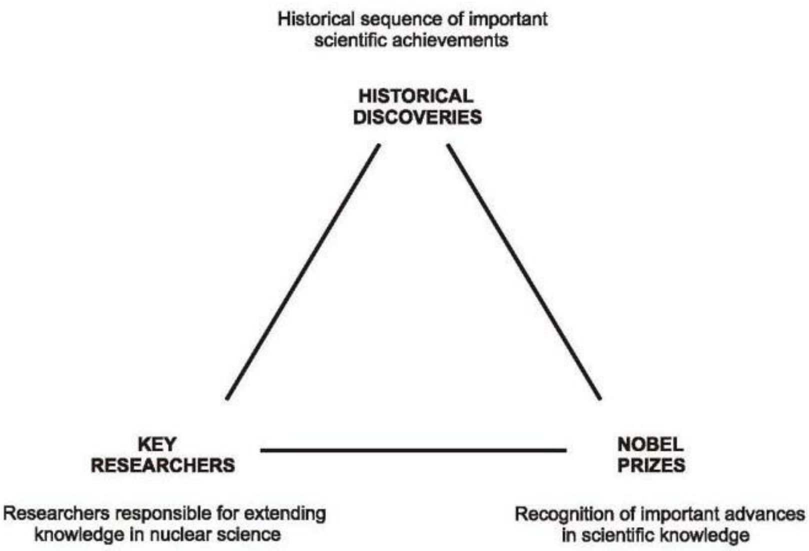

Figure 1. Evolution of scientific advancement

In reviewing this evolution of nuclear energy it is as well to note the recognition given to the researchers responsible for these discoveries and the Nobel Prize is the most prestigious award given to such advances in the scientific field. Some twenty Nobel

Prizes in nuclear and radiation physics and nuclear chemistry or closely related fields were awarded over a fifty year period from 1901 the year of the first Nobel Prize.

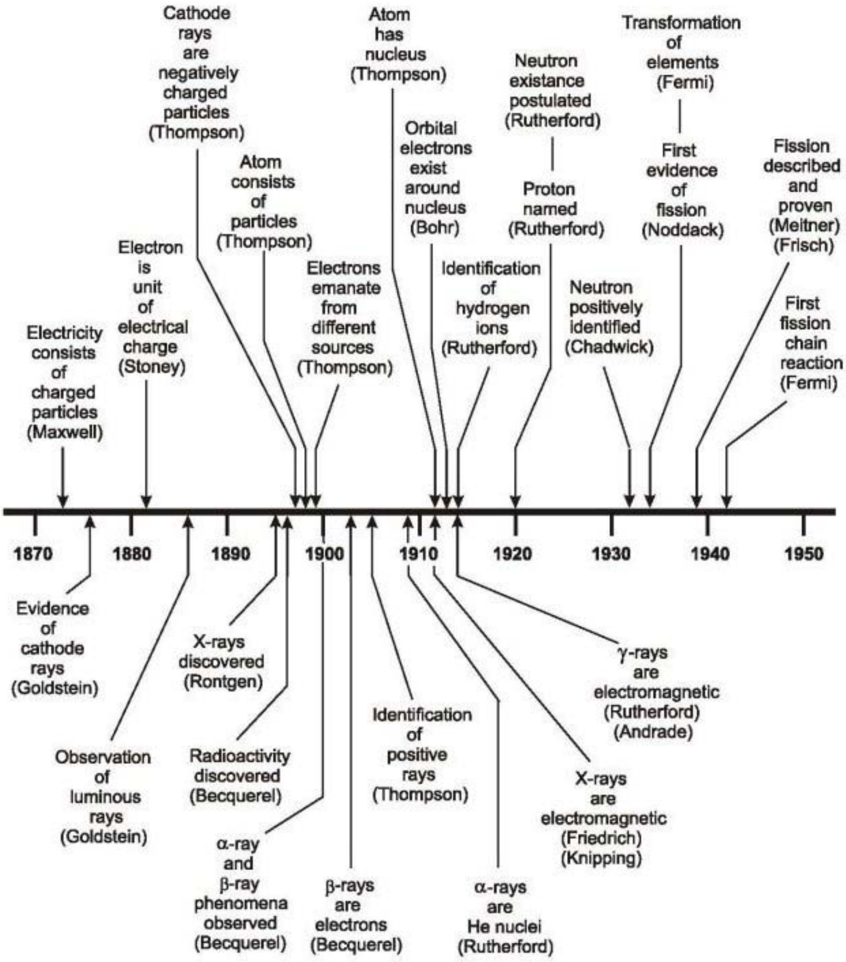

Figure 2. Timeline of significant discoveries

While electrical phenomena had been studied early in the nineteenth century it was only near the turn of the century that radiation was discovered. This was followed rapidly in the early twentieth century in establishing the structure of the atom and differentiating the types of radiation. Following research on the effect of neutrons on atoms and the resulting splitting of the atom, it became evident that neutrons could produce a fission chain reactor leading to the release of energy. This enabled the first research reactor and subsequent power reactors to be built. This section, derived from the *Sourcebook on Atomic Energy* by Samuel Glasstone, gives an outline of the development of this technical knowledge. The timeline of these discoveries is shown in Figure 2.

1.2. The Atom

1.2.1. Electron

Early experiments of electrical discharges in rarefied gases by Plücher showed a green glow in the glass tube in the vicinity of the cathode. Subsequently these were assumed to be caused by rays which were consequently called *cathode rays* by Goldstein in 1876. Thompson with better equipment showed that cathode rays were in fact streams of negatively charged particles in 1897.

Following experiments on electrolysis by Faraday and subsequent study by Maxwell, Maxwell suggested in 1873 that electricity consisted of discrete molecular type charges. Later in 1874 Stoney noted that such charges were related to the chemical bonding of elements in an electrolyte. These charges were accepted as being the smallest known particle of electricity and Stoney in 1881 proposed the name *electron* for the elementary unit of charge. Thompson showed in 1899 that electrons could be generated from different sources and were particles with a given mass and charge which could be related to the mass and charge of a hydrogen atom. They were therefore fundamental constituents of all atoms.

1.2.2. Proton

In 1886 Goldstein had observed luminous rays emitted behind a perforated cathode. These were found by Perrin in 1895 to carry a positive charge. It was proposed by Thompson in 1907 that these be called *positive rays*. It was subsequently found by Rutherford in 1914 that the particles making up these rays in hydrogen gas were in fact hydrogen ions. By 1920 it was realized that the positively charged hydrogen ion was an important unit in the structure of atoms and it was given the name *proton*.

1.2.3. Neutron

In 1920 Rutherford and others suggested that an uncharged particle resulted from the neutralization of the electrical charge on a proton by an electron. This hypothetical particle was called a *neutron*. Chadwick proved in 1932 that neutrons did exist and showed that the results of other experimenters in this field could be fully explained.

1.2.4. Atom

Thompson in 1898 suggested that atoms consist of a large number of corpuscles (electrons) to form a system which is neutral. He elaborated on this theme in 1904 in suggesting that there was positive electrification and that the corpuscles (electrons) were arranged in a series of shells as illustrated by the periodic table. Also in 1904 Nagaoka compared the atom with the planet Saturn and its satellites where the negative electrons were attracted to a heavy positive central body. Thompson deduced in 1912, from scattering experiments with α-particles, that the positive charge in the atom was concentrated in a small region, which he called the *nucleus*, at the centre of the atom. The concept of electrons rotating around a positive nucleus could not be reconciled with electromagnetic theory which dictated that energy should be emitted by the rotating electrons. Bohr however suggested in 1913 that such a closed orbit on an atomic scale was a stationary state and thus stable. Moreover several stationary states of constant energy were possible and that energy was only emitted in the jump of an electron from one stationary state to another. Although the ideas of Bohr appeared contradictory to conventional theory he was able to relate the energy emitted to Plank's theory relating energy and wavelength. Bohr's model of the atom subsequently fitted well with quantum theory and became the standard model for describing atomic structure.

1.3. Radiation

1.3.1. X-rays

While experimenting with evacuated glass tubes in which cathode rays produced luminescence, Roentgen discovered in 1895 that luminescence was also produced in other materials even outside the tubes. He concluded that penetrating rays which he called *x-rays* were being emitted. Although others had observed the effect on photographic plates Roentgen was the first to recognize the source of the effect and to actually use the phenomena to take photographs through opaque objects. X-rays were considered something of a mystery until 1912 when it became evident that they were electromagnetic radiation of short wave length. X-rays are caused by a stream of high energy electrons impinging upon a suitable material.

1.3.2. Radioactivity

While experimenting with fluorescence, Becquerel discovered in 1896 that a uranium salt emitted radiation similar to that of X-rays. Subsequently several other elements were found to emit similar radiation and that the air in the vicinity of the radiation was ionized in some manner. Such elements exhibited *radioactivity*.

1.3.3. Beta-Particles

Rutherford, while studying the ionizing power of radiation, concluded that there were two types of radiation with different penetrating power. These he called alpha (α) rays and beta (β) rays with the latter able to penetrate a hundred times further than the former. Similar conclusions were made by Pierre and Marie Curie in 1900. Becquerel subsequently determined the charge on β-rays and found that β-rays, like cathode rays consisted of negatively charged electrons hence the name β-*particles*.

1.3.4. Alpha-Particles

Rutherford concluded in 1903 that alpha rays were very similar to the positive rays observed earlier in experiments with electrical discharges. In 1906 more accurate measurements indicated that alpha rays were indeed particles and in 1908 Rutherford and Geiger showed that alpha rays were likely a stream of helium nuclei. This was confirmed in 1909 hence the name α-*particles*. An α-particle when picking up two electrons became an atom of helium

1.3.5. Gamma-Radiation

Gamma (γ) rays were discovered by Villard in 1900 but only after diffraction of these rays by a suitable crystal did Rutherford and Andrade show in 1914 that they were in fact waves. These γ-*rays* form part of the electromagnetic spectrum.

1.4. Nuclear Fission

Prior to 1939 there was no evidence to suggest the practical utilization of atomic energy. In 1934 Fermi had reported that when uranium was subjected to a stream of neutrons elements of higher mass number were formed. These transuranic elements attracted the interest of other researchers who discovered elements of unexpected mass numbers in the products. Hahn and Strassmann noted in 1938 that the masses of two of these products added up to the mass of the uranium atom plus a neutron. Subsequently in early 1939 Meitner and Frisch were able to explain in a published report that "It seems possible that the uranium nucleus has only small stability of form and may, after neutron capture, divide itself into two nuclei of roughly equal size". This was called *fission* as was commonly used in biological terms to describe the division of living cells. Frisch soon after proved, as they had predicted, that the particles released had strong ionizing power. This was also confirmed by several other researchers. Furthermore these fission fragments were found to be ejected at high velocity and to posses radioactive properties. Most of the confirmatory work of this new revelation was completed within three months of the initial publication of the theory of nuclear fission. This subsequently was generally referred to as "splitting the atom".

Meitner and Frisch estimated that the amount of energy release in a single fission process was in the order of 200 MeV, far greater than any other known nuclear reaction. This can be shown by comparing the masses of the fission products with the masses of the original nucleus plus a neutron and converting this difference to energy.

It soon became evident, as had been mentioned by Fermi, that neutrons should be emitted during fission due to the general structure of the atoms of uranium and the fission products. This was subsequently confirmed by different researchers.

1.5. Nuclear Energy

It had been recognized that mass could be converted into energy and that so called sub-atomic particles existed within atoms. When nuclear fission by neutrons was discovered and found to produce further neutrons along with the fission fragments, the possibility of a branching chain of fissions became a new prospect. If this occurred in a rapid sequence, with the amounts of energy found to be released with each fission, the result could lead to a catastrophic explosion. At that time interest became focused on the possibility of a powerful atomic bomb. Subsequently from 1940 all further work related to the utilization of nuclear energy to produce an atomic bomb took place in secrecy. The limits to this possibility became evident with further research that showed that a nuclear chain reaction could only be sustained in Uranium-235 and Plutonium-239. The former could be separated by gaseous diffusion and the latter created by a controlled neutron chain reaction. Both methods required extensive equipment to produce even small amounts.

The production of Pu-239 required an operating nuclear reactor with suitable fuel and moderator to establish a chain reaction with U-235 in which neutrons were produced, some of which would be absorbed in U-238 to create Pu-239. In order to construct a reactor in which a controlled chain reaction would occur, Fermi and Szilard realized that a heterogeneous system of lumps of uranium embedded in graphite blocks in lattice formation would be required. The first experimental lattice was erected in 1941 at Columbia University under the supervision of Fermi and followed by a larger one shortly thereafter, but impurities in the materials prevented a chain reaction from being initiated. Towards the end of 1942 sufficient amounts of pure materials were available and a sufficiently large pile of graphite blocks and lumps of uranium was built at the University of Chicago to establish a continuous self sustaining chain reaction on 2 December 1942.

The next step was an enormous scale up to the plutonium production plants at Hanford Works where sufficient plutonium was produced to enable the first atomic bomb to be tested on 16 July 1945.

1.6. Nuclear Reactors

Nuclear reactors can be broadly classified into three main categories

- Research reactors
- Production reactors
- Power reactors

The first reactors that were built were generally research reactors but, as part of the Manhattan Project, there was an incentive to quickly develop production reactors for producing plutonium for atomic bombs. Subsequently some production reactors served the dual purpose of producing electric power as well as plutonium. Materials testing was an important function of early research reactors when the effects of neutron activation and γ-ray irradiation on various materials were being studied. More recently the role of research reactors has become more that of production reactors with the increasing need for production of radioactive isotopes for industrial and food irradiation and medical diagnosis and treatment purposes. Power reactors primarily produce electric power though a few are used for propulsion purposes in naval vessels. The design and operation of these reactors in the three categories is different in order to serve different purposes.

1.6.1. Research Reactors

The first reactor, built at the University of Chicago and in which a self sustaining nuclear chain reaction was achieved in 1942, was a research reactor to prove the concept. It operated for only a short period at a power of only 200 W. In the following years other reactors were built in the United States, Canada and the United Kingdom with different configurations and increasing power outputs in order to develop the technology and to test various concepts and materials. Most were of relatively small size and with low power outputs.

1.6.2. Production Reactors

The first reactors built at the Hanford Works in the United States were for the production of plutonium. To produce fissile Plutonium-239 a high neuron flux is required so as to minimize the time of irradiation of Uranium-238. Furthermore the fuel should not be irradiated for too long otherwise an excessive amount of neutron absorbing and non-fissile Plutonium-240 builds up by neutron absorption in Pu-239. A fairly high rate of fuel throughput is therefore required. The fission process in Uranium-235 to produce the necessary neutron flux also generates a considerable amount of heat which can be used for power generation. The plutonium producing reactors at Calder Hall and Chapelcross in the United Kingdom made use of this heat to generate power. Calder Hall thus became the first nuclear plant in the world to generate electric power on a commercial scale in 1956.

Isotope production reactors also require a high flux which was initially achieved by utilizing highly enriched uranium (~ 90% U-235). More recently however, because of the concerns regarding diversion of highly enriched uranium for building atomic weapons, designs have been modified to allow the use of low enriched uranium (< 20% U-235) while still providing adequate neutron fluxes. Furthermore isotopes are produced outside the fuel by irradiation and irradiation times are very variable. This makes it necessary to have continuous but remote access to the reactor core during operation. Low temperatures are therefore desirable and most isotope producing reactors operate with light water serving the function of moderator, coolant and radiation shield. This not only allows samples to move in and out of the radiation field relatively easily but also facilitates remote handling and limited visual observation.

1.6.3. Power Reactors

The primary purpose of power reactors is to produce electric power. Although some reactors, such as those built at Calder Hall and Chapelcross, served the alternative purpose of producing plutonium there is a penalty in a high fuel throughput in order to do this. Therefore nearly all power reactors make use of the plutonium built up in the fuel to produce additional power within the reactor.

Calder Hall was the first reactor to produce electric power commercially. Subsequently the graphite moderated gas cooled reactor concept was commercially developed in the United Kingdom resulting in a series of nuclear power plants which generated a significant portion of the country's electric power. Shippingport, commissioned in 1957, was the first nuclear plant in the United States to generate electric power on a commercial scale. It was of the pressurized water reactor type using light water as a moderator and coolant with steam produced in a separate steam generator. This type has become the dominant type with approximately half of the reactors in the world being of this design. Dresden, also in the United States and commissioned in 1960, was the first full scale privately financed nuclear plant in the United States thus establishing nuclear power as a viable and competitive source of energy. It was of the boiling water reactor type using light water as a moderator and coolant with steam produced directly in the reactor core by boiling under pressure. This is the second most common type of reactor in the world.

Power reactors for transportation have been limited to naval vessels such as submarines and aircraft carriers which have to remain at sea for extensive periods. These are all of the pressurized water type with the first being commissioned on the United States submarine, the Nautilus, in 1955.

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Biographical Sketch

Robin Chaplin obtained a B.Sc. and M.Sc. in Mechanical Engineering from University of Cape Town in 1965 and 1968 respectively. Between these two periods of study he spent two years gaining experience in the operation and maintenance of coal fired power plants in South Africa. He subsequently spent a further year gaining experience on research and prototype nuclear reactors in South Africa and the United

Kingdom and obtained M.Sc. in Nuclear Engineering from Imperial College of London University in 1971. On returning to South Africa and taking up a position in the Head Office of Eskom he spent some twelve years initially in project management and then as Head of Steam Turbine Specialists. During this period he was involved with the construction of the 3 x 80 MW Ruacana Hydro Power Station in Namibia and the 2 x 900 MW Koeberg Nuclear Power Station in South Africa being responsible for the underground mechanical equipment and civil structures and for the mechanical balance-of-plant equipment at the respective plants. Continuing his interests in power plant modeling and simulation he obtained a Ph.D. in Mechanical Engineering from Queen's University in Canada in 1986 and was subsequently appointed as Chair in Power Plant Engineering at the University of New Brunswick. Here he teaches thermodynamics and fluid mechanics and specialized courses in nuclear and power plant engineering in the Department of Chemical Engineering. An important function is involvement in the plant operator and shift supervisor training programs at Point Lepreau Nuclear Generating Station. This includes the development of material and the teaching of courses in both nuclear and non-nuclear aspects of the program. He has also been involved with the UNESCO sponsored Encyclopedia of Life Support Systems (EOLSS) as Honorary Theme Editor and primary author of the theme on Thermal Power Plants and has also assisted with the theme on Nuclear Energy and Reactors. Altogether he has contributed some three dozen chapters to this major source of international knowledge. As an adjunct professor at Waterloo University he has established and taught a graduate course in power plant thermodynamics to engineers in the nuclear industry as part of the UNENE masters program in Nuclear Engineering. He has served as Acting Chair and Chair in the Department of Chemical Engineering at University of New Brunswick and has been a consultant for Canadian Power Utility Services.