Historical Background

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Summary:

A review of the historical background for the development of nuclear energy is given to set the scene for the discussion of CANDU reactors.

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1 Growth of Science and Technology

The rate of technology increase has accelerated as technology itself has increased, leading to a sort of exponential growth. Energy growth is a good example of this phenomenon. Water power developed relatively slowly, steam power somewhat more quickly, electrical power even more rapidly, and nuclear power very rapidly. In the case of nuclear energy, collaboration between scientists in different countries initially spurred the discovery of various nuclear particles. Then the Second World War provided an incentive to harness the fission process, and later the rapid growth in demand for new energy after the war provided the need for nuclear power. Within the time span of roughly half a century, an entirely unknown source of energy had become a major producer of commercial electric power. In addition, an entirely new and sophisticated technology had been developed.

Before about 1900, most scientific work in this field was related to electricity. Then in the next two decades following the discovery of radiation and its characteristics, various pieces of the nuclear puzzle began to come together. Only by 1920 was the basic structure of the atom understood, and the existence of the neutron was confirmed in 1932. This was a pivotal discovery because 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.

In reviewing this evolution of nuclear energy, it is important to note the recognition given to the researchers responsible for these discoveries. 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.

To appreciate these advances in technology properly, it is convenient to consider a timeline of achievement with key advances shown and to link these with some renowned scientists. A timeline of these discoveries is shown in Figure 1.

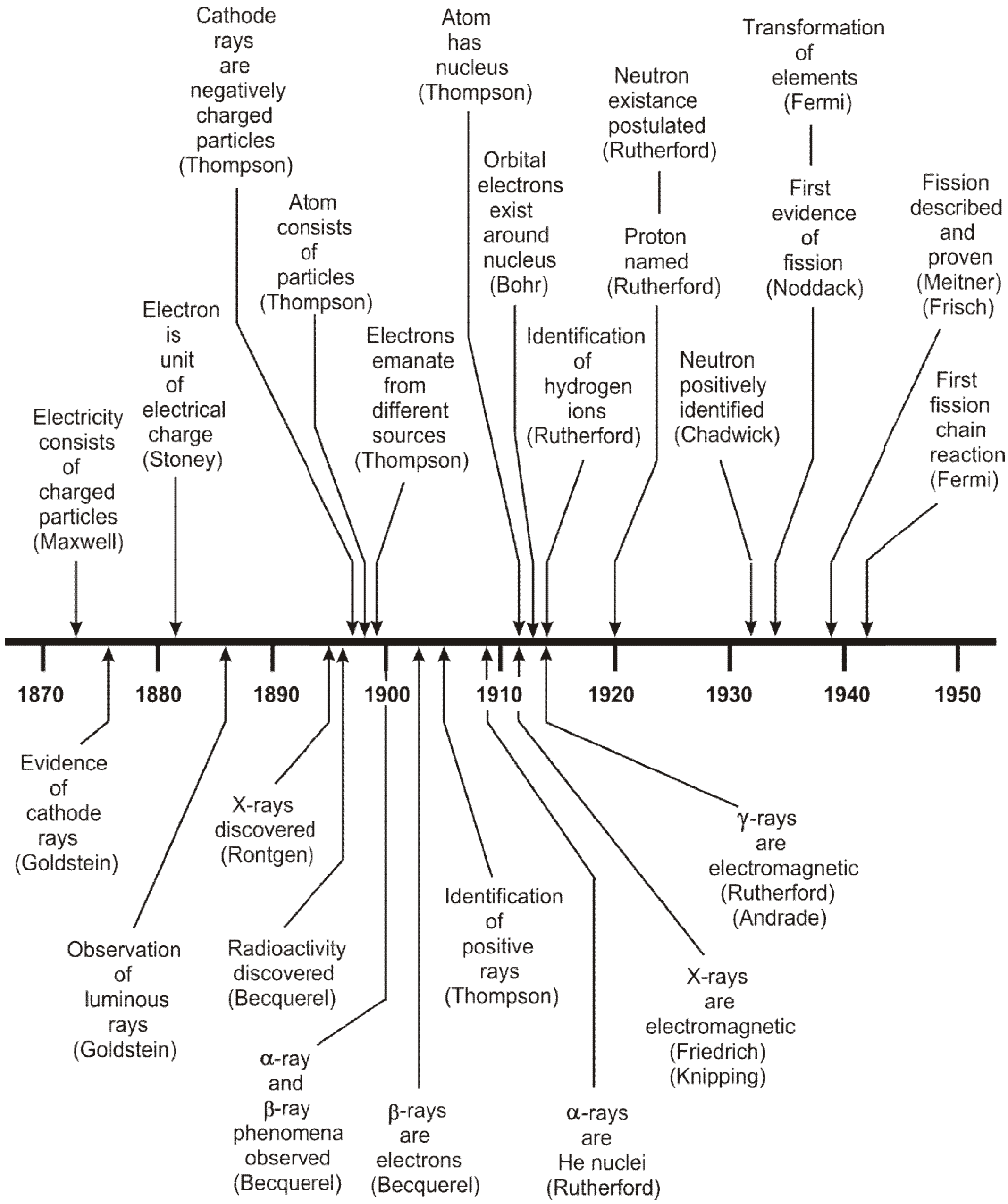

Figure 1 Timeline of significant discoveries

2 Renowned Scientists

Many researchers in different countries around the world have contributed to this new field of science. Several collaborated with one another or worked or were trained in another's laboratory. Each contributed a piece of the puzzle. Those making a significant advancement in this field were awarded Nobel Prizes. Some 20 prizes were awarded over a fifty-year period, demonstrating the importance of this field of science.

The Nobel Prizes awarded in Physics and Chemistry in the nuclear field from 1901 to 1951 with the recipients and a statement of their contribution, as obtained from the *Nobel Foundation Official Web Site,* are listed below.

1901	Physics:	*Wilhelm Conrad Roentgen* "In recognition of the extraordinary services he has rendered by the discovery of the remarkable rays subsequently named after him"
1903	Physics:	*Antoine Henri Becquerel* "In recognition of the extraordinary services he has rendered by his discovery of spontaneous radioactivity" *Pierre Curie, Marie Curie (née Sklodowska)* "In recognition of the extraordinary services they have rendered by their joint researches on the radiation phenomena discovered by Professor Henri Becquerel"
1906	Physics:	*Joseph John Thomson* "In recognition of the great merits of his theoretical and experimental investigations on the conduction of electricity by gases"
1908	Chemistry:	*Ernest Rutherford* "For his investigations into the disintegration of the elements, and the chemistry of radioactive substances"
1911	Chemistry:	*Marie Curie (née Sklodowska)* "In recognition of her services to the advancement of chemistry by the discovery of the elements radium and polonium, by the isolation of radium and the study of the nature and compounds of this remarkable element"
1918	Physics:	*Max Karl Ernst Ludwig Planck* "In recognition of the services he rendered to the advancement of Physics by his discovery of energy quanta"
1921	Physics:	*Albert Einstein* "For his services to Theoretical Physics, and especially for his discovery of the law of the photoelectric effect"
1922	Physics:	*Niels Henrik David Bohr* "For his services in the investigation of the structure of atoms and of the radiation emanating from them"

1923	Physics:	*Robert Andrews Millikan* "For his work on the elementary charge of electricity and on the photoelectric effect"
1927	Physics:	*Arthur Holly Compton* "For his discovery of the effect named after him" *Charles Thomson Rees Wilson* "For his method of making the paths of electrically charged particles visible by condensation of vapour"
1929	Physics:	*Prince Louis-Victor Pierre Raymond de Broglie* "For his discovery of the wave nature of electrons"
1932	Physics:	*Werner Karl Heisenberg* "For the creation of quantum mechanics, the application of which has, inter alia, led to the discovery of the allotropic forms of hydrogen"
1933	Physics:	*Erwin Schrödinger*, *Paul Adrien Maurice Dirac* "For the discovery of new productive forms of atomic theory"
1935	Physics:	*James Chadwick* "For the discovery of the neutron"
1938	Physics:	*Enrico Fermi* "For his demonstrations of the existence of new radioactive elements produced by neutron irradiation, and for his related discovery of nuclear reactions brought about by slow neutrons"
1939	Physics:	*Ernest Orlando Lawrence* "For the invention and development of the cyclotron and for results obtained with it, especially with regard to artificial radioactive elements"
1944	Chemistry:	*Otto Hahn* "For his discovery of the fission of heavy nuclei"
1945	Physics:	*Wolfgang Pauli* "For the discovery of the Exclusion Principle, also called the Pauli Principle"
1951	Physics:	*Sir John Douglas Cockcroft* *Ernest Thomas Sinton Walton* "For their pioneer work on the transmutation of atomic nuclei by artificially accelerated atomic particles'
1951	Chemistry:	*Edwin Mattison McMillan, Glenn Theodore Seaborg* "For their discoveries in the chemistry of the transuranium elements"

3 Significant Achievements

Three scientists and their respective discoveries tend to stand out in the development of nuclear physics as applied to energy production. Niels Bohr developed a model to describe the structure of the atom, James Chadwick established the existence of neutrons, and Enrico Fermi directed the construction of the first reactors. All these achievements were the result of extensive work in analyzing the results and further developing the ideas of other researchers and collaborators. Extracts of their biographies from the *Nobel Foundation Official Web Site* are given below.

3.1 Niels Bohr

In the autumn of 1911 he made a stay at Cambridge, where he profited by following the experimental work going on in the Cavendish Laboratory under Sir J.J. Thomson's guidance, at the same time as he pursued his own theoretical studies. In the spring of 1912 he was at work in Professor Rutherford's laboratory in Manchester, where just in those years such an intensive scientific life and activity prevailed as a consequence of that investigator's fundamental inquiries into the radioactive phenomena. Having there carried out a theoretical piece of work on the absorption of alpha rays which was published in the *Philosophical Magazine,* 1913, he passed on to a study of the structure of atoms on the basis of Rutherford's discovery of the atomic nucleus. By introducing conceptions borrowed from the Quantum Theory as established by Planck, which had gradually come to occupy a prominent position in the science of theoretical physics, he succeeded in working out and presenting a picture of atomic structure that, with later improvements (mainly as a result of Heisenberg's ideas in 1925), still fitly serves as an elucidation of the physical and chemical properties of the elements.

3.2 James Chadwick

In 1932, Chadwick made a fundamental discovery in the domain of nuclear science: he proved the existence of *neutrons*—elementary particles devoid of any electrical charge. In contrast with the helium nuclei (alpha rays) which are charged, and therefore repelled by the considerable electrical forces present in the nuclei of heavy atoms, this new tool in atomic disintegration need not overcome any electric barrier and is capable of penetrating and splitting the nuclei of even the heaviest elements. Chadwick in this way prepared the way towards the fission of uranium 235 and towards the creation of the atomic bomb. For this epoch-making discovery he was awarded the Hughes Medal of the Royal Society in 1932, and subsequently the Nobel Prize for physics in 1935.

3.3 Enrico Fermi

In 1934, Fermi evolved the β-decay theory, coalescing previous work on radiation theory with Pauli's idea of the neutrino. Following the discovery by Curie and Joliot of artificial radioactivity (1934), he demonstrated that nuclear transformation occurs in almost every element subjected to neutron bombardment. This work resulted in the discovery of slow neutrons that same year, leading to the discovery of nuclear fission and the production of elements lying beyond what was until then the Periodic Table.

In 1938, Fermi was without doubt the greatest expert on neutrons, and he continued his work on this topic on his arrival in the United States, where he was soon appointed Professor of Physics at Columbia University, N.Y. (1939-1942).

Upon the discovery of fission, by Hahn and Strassmann early in 1939, he immediately saw the possibility of emission of secondary neutrons and of a chain reaction. He proceeded to work with tremendous enthusiasm, and directed a classical series of experiments which ultimately led to the atomic pile and the first controlled nuclear chain reaction. This took place in Chicago on December 2, 1942, on a squash court situated beneath Chicago's stadium. He subsequently played an important part in solving the problems connected with the development of the first atomic bomb. (He was one of the leaders of the team of physicists on the Manhattan Project for the development of nuclear energy and the atomic bomb).

4 Nuclear Fission

Before 1939, there was no evidence to suggest the practical usefulness of atomic energy. In 1934, Enrico 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. Otto Hahn and Friedrich 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, Lise Meitner and Otto 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*, the term which was commonly used in biology to describe the division of living cells. Otto 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 possess 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".

Lise Meitner and Otto 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 Enrico 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.

5 Nuclear Energy

It had already 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 fission fragments, the possibility of a branching chain of fissions became a real prospect. If these occurred in a rapid sequence, given the amount of energy released in each fission event, the result could be a catastrophic explosion. At that time, interest became focused on the possibility of a powerful atomic bomb. Subsequently, from 1940 on, all further work related to the use 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 be sustained only 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. To construct a reactor in which a controlled chain reaction would occur, Enrico Fermi and Leo Szilard realized that a heterogeneous system of lumps of uranium embedded in graphite blocks in a 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 December 2, 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 July 16, 1945. Concurrently, a huge gaseous diffusion plant was built at Oak Ridge to separate U-235 from U-238 and so create highly enriched uranium for a second atomic bomb.

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