

An introduction to the **CANDU**
NUCLEAR ENERGY
CONVERSION
SYSTEM

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FORWORD

The CANDU nuclear reactor has recently attracted considerable attention both at home and abroad. The increasing interest in this distinctly Canadian nuclear energy system has identified the need for an introductory description of the basic elements of the CANDU reactor suitable for a readership with a wide range of professional qualifications.

It is believed that this monograph can serve as a self-study guide and as a supportive text for the scientist, engineer and other technically oriented individual with little previous exposure to nuclear engineering in general and who possesses only a passing familiarity with the CANDU nuclear reactor in particular. An attempt has been made to be impressionistic on both the analytical-scientific and the systems-descriptive level. A detailed discussion of specialized topics such as reactor physics, plant engineering and reactor operations is outside the scope of this text.

Most of the material contained here has been extracted from various non-proprietary documents published by Atomic Energy of Canada Ltd. Several professional and technical staff members of AECL's Power Projects Division have been most helpful in providing suggestions and in the preparation of the figures. This support is gratefully acknowledged.

This version of the monograph is a controlled circulation issue designed, in part, to solicit further comments and suggestions.

A.A. Harms
January 1975

CHAPTER 1

INTRODUCTION

Energy, in its various forms, has been found to be a basic resource by mankind. It is essential in the supply of comfort heat and health care services; it is a necessary ingredient in the production of agricultural products, clothing materials, and industrial goods. Indeed, there are few things in man's physical existence which at some time are not affected by energy in at least one of its various forms.

1.1 ENERGY CONVERSION

When early man burned wood to keep warm and to prepare food, he made use of a form of energy conversion. Although this form of energy conversion constituted a major resource of useful energy even as late as the 1850's, changes in technology associated with man's interest in a more efficient and convenient form of energy supply led to significant changes in energy conversion technology. By the end of the nineteenth century, coal had replaced wood as the dominant resource. Several decades later a most extensive use of petroleum products was made in an increasingly complex system of transportation and manufacturing. More recently it has become evident that the limited oil and gas resources will need to be supplanted by energy from nuclear sources.

A cursory examination of the world reserves of basic energy resources provides some significant indication about energy conversion patterns to be expected in the long term. Using the symbol Q as a unit of energy defined by

$$1Q = 10^{18} \text{ British Thermal Units} = 0.2 \times 10^{21} \text{ Joules,}$$

it has been estimated that the world energy reserves from various sources vary from a few to thousands of Q 's. Table 1.1 provides the appropriate summary data. Recognizing that the current rate of world energy consumption is approximately $0.2Q$ per year clearly suggests that nuclear energy conversion will need to be relied upon even in the intermediate term.

1.2 BASICS OF NUCLEAR ENERGY

In the burning of coal and in the combustion of gasoline, energy is released as

a consequence of a chemical recombination of some constituent atoms; carbon in coal or gasoline combines with oxygen in air and, in the process, releases energy which appears in the form of heat. In a related, but physically distinct process, nuclear energy is released as a consequence of a recombination of neutrons and protons of some constituent nuclei.

Oil and Gas.....	~ 5 Q
Coal.....	~30 Q
Uranium and Thorium.....	~10,000 Q

TABLE 1.1: Estimated world energy reserves. The current consumption is estimated at 0.2 Q per year. (1 Q = 10^{18} BTU = 0.2×10^{21} Joules).

Atomic and nuclear theory provides the basis for a rational understanding of nuclear processes. The atomic nucleus consists of a number of protons, commonly designated by the symbol Z , a number identifying a given nucleus A , which is equal to the number of protons and neutrons, $A = Z + N$, and the name of the element X which is associated with a specific number of protons Z . Symbolically this is written as ${}^A X$; that is

${}^A X$ = a nucleus identified by name of the element X associated with Z protons and $N = A - Z$ neutrons.

An element named "X" associated with a specific number of protons Z , can exist with a varying number of neutrons; thus the atomic number A may change. This change in atomic number of a given element identifies a nuclear specie called isotope. For example, the element uranium exists in nature in the isotopic forms and abundances listed in Table 1.2.

Name and Symbol of Nuclide	Natural Isotopic Abundance	Number of Protons Z	Number of Neutrons N	Atomic Mass Number $A = Z + N$
${}^{234}\text{U}$ (Uranium-234)	0.0056%	92	142	234
${}^{235}\text{U}$ (Uranium-235)	0.7205%	92	143	235
${}^{238}\text{U}$ (Uranium-238)	<u>99.2739%</u>	92	146	238
	100.0000%			

TABLE 1.2: Isotopic abundance and nuclear composition of uranium.

Even though these three uranium nuclei have similar chemical properties, they differ most profoundly with respect to their nuclear properties. For example, a neutron possessing a relatively low velocity is far more likely to be absorbed by Uranium-235 than by any one of the other naturally occurring uranium isotopes. Indeed, it is this absorption of a neutron in certain nuclei and the subsequent effects which are central to the release of nuclear energy.

Early in the study of nuclear reactions, it was discovered that Uranium-235 belongs to a group of nuclei which possess a remarkable feature associated with neutron absorption: this Uranium-235 nucleus - which upon the absorption of a neutron is properly identified as Uranium-236 - will, with a very high probability, break up into two fragments of unequal mass and concurrently release several neutrons; in addition, various forms of radiation will be emitted either immediately or at various times. Figure 1.1 provides a graphical representation of this fission process. A fundamental feature in this reaction is the observation that the mass of all the resultant nuclear fragments possesses a lesser total mass than the initial uranium nucleus, together with the incident neutron. This loss of mass, called the mass defect, Δm , when substituted into Einstein's relation which relates mass to energy

$$E = (\Delta m)c^2 \quad (1.1)$$

represents the total energy thus released and potentially made available for useful purposes; in this equation, c represents the speed of light. In excess of 80% of this energy appears in the form of kinetic energy of the two fission products. As these fission products move through matter they transfer their kinetic energy to the surrounding atoms which result in an increase in temperature of the nuclear fuel. The subsequent transfer of thermal energy from the hot nuclear fuel to the coolant and subsequently to the appropriate energy exchange systems such as heat exchangers, steam turbines and electric generators, completes the process whereby nuclear energy is converted into a form most useful for domestic and manufacturing purposes. The fission neutrons which appear during the fission process proceed to initiate further fissions and thus provide conditions for the continuous release of nuclear energy.

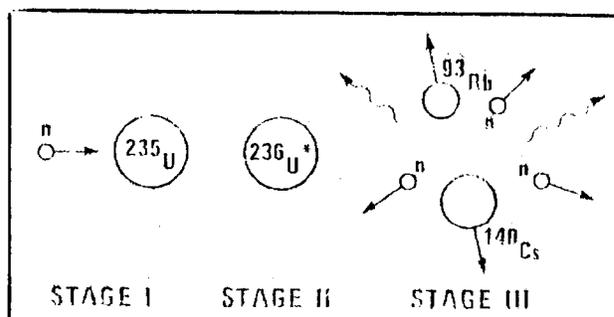


FIG. 1.1: Graphical representation of neutron induced fission in Uranium-235. The fission products Rubidium-93 and Cesium-140 are shown here although other fission products may emerge. Three high energy fission neutrons (n) and other radiations are also shown.

1.3 NUCLEAR ENERGY DEVELOPMENT IN CANADA

Canada's concentrated research and developmental program in nuclear energy had its beginning in the early 1940's when Canada joined with the United Kingdom and the United States in some investigations on neutron multiplication and neutron migration with particular emphasis on uranium in graphite and in water. This early work was conducted initially in Montreal, Quebec, and subsequently in Chalk River, Ontario, as an activity of the National Research Council of Canada.

The investigation of nuclear phenomena in Canada together with similar work pursued in the U.K. and U.S.A., soon led to the identification of several fundamental features of neutrons which appear as a result of the fission process

1. The several neutrons which appear as a result of the fission process in uranium possess a relatively high kinetic energy.
2. Low energy neutrons are more effective in inducing nuclear fission than high energy neutrons.
3. High energy neutrons lose energy by elastic scattering with nuclei in a manner similar to billiard-ball type collisions.
4. When a neutron undergoes a collision with a nucleus, there is a definite probability that the neutron may be captured.
5. Due to the few neutrons which appear in a fission process, it is paramount that neutrons be conserved to insure that a self-sustaining reaction be maintained.

Following a study of the number of neutrons emitted in the fission of fissile nuclei and an investigation of suitable materials which could be used to slow neutrons down with a minimum likelihood of capture, it became evident that the combination of uranium in its natural isotopic abundance as the nuclear fuel combined with heavy water as the neutron slowing down agent, commonly called the moderator, represent a combination with significant technical and economic features.

1. Although Uranium-235 is the only naturally occurring uranium isotope which will readily fission by low energy neutrons, the separation of this isotope from natural uranium involves significant technical problems and considerable cost. The use of uranium in its natural isotopic composition as the fuel is thus most appealing and more so since Canada possesses ample supplies of uranium-bearing ore.
2. Heavy water (D_2O), a liquid which is chemically similar to light water (H_2O), is an excellent neutron moderating agent. Although heavy water is not as effective in slowing energetic neutrons down during each elastic scattering collision as light water, it possesses a substantially lesser likelihood of capturing the neutrons. On this account heavy water constitutes a superior moderator.

These two considerations, uranium as the nuclear fuel and heavy water as

the moderator, characterize the Canadian nuclear energy conversion system identified by the generic name CANDU (CANadian-Deuterium-Uranium). We note that this name does not specify the type of coolant to be used; this distinction will again be referred to later.

Following a decade of active nuclear research, the division of the National Research Council which was specifically concerned with nuclear energy was designated a crown corporation in 1952 and named Atomic Energy of Canada Limited (AECL). In subsequent years, AECL undertook extensive research and pursued an active developmental and design program on all peaceful aspects of nuclear energy based on the natural uranium and heavy water combination. Although its initial activity was based at the Chalk River Nuclear Laboratories, it soon established other centers as its mission expanded. By 1974, research development and design activity was conducted at the following divisional installations:

1. Chalk River Nuclear Laboratories, Chalk River, Ontario.
Activity: Research and Development.
Staff: 500 Professional, 600 Technical, 1300 Support.
2. Whiteshell Nuclear Research Establishment, Pinawa, Manitoba.
Activity: Research and Development.
Staff: 200 Professional, 250 Technical, 400 Support.
3. Commercial Products, Ottawa, Ontario.
Activity: Isotopes and Irradiation.
Staff: 100 Professional, 100 Technical, 300 Support.
4. Power Projects,
 - (a) Sheridan Park, Ontario.
Activity: Nuclear Power Plant Design and Consulting.
 - (b) Peterborough, Ontario.
Activity: Nuclear Fuel Handling.
Combined Staff: 300 Professional, 400 Technical, 200 Support.
5. Heavy Water Projects, Ottawa, Ontario.
Activity: Heavy Water Production.
Staff: 30 Professional, 20 Support.

Plans to establish another branch of the Power Projects to be located in Montreal have been initiated in 1974. The administration offices of AECL are located in Ottawa.

It is important to note that although AECL is charged with the development of nuclear reactors in Canada, all regulatory and licensing aspects associated with nuclear facilities in Canada are vested with the Atomic Energy Control Board (AECB),

During the period from the inception of nuclear energy research in 1942 up to 1965, AECL and its NRC predecessor built and operated six test and research reactors specifically designed in support of its research and developmental program. The reactors varied in power from a small ambient-air cooled reactor (ZEEP) to a large 100 MW reactor (NRU); these facilities served a variety of purposes and were designed to perform various functions, Table 1.3.

Name	Date Completed	Location	Power	Type and Purpose
ZEEP	1945	Chalk River, Ontario	<100W	D ₂ O-moderated; lattice experiments.
NRX	1947	Chalk River, Ontario	30W	D ₂ O-moderated, H ₂ O-cooled; research, engineering and isotope production.
NRU	1957	Chalk River, Ontario	100MW	D ₂ O-moderated, D ₂ O-cooled; research, engineering and isotope production.
PTR	1957	Chalk River, Ontario	10kW	Highly enriched pool reactor; swing measurements of reactivity.
ZED-2	1960	Chalk River, Ontario	150W	D ₂ O-moderated; lattice experiments.
WR-1	1965	Pinawa, Manitoba	60MW	D ₂ O-moderated, organic-cooled; research and engineering.

TABLE 1.3: Canadian test and research nuclear reactors.

We injected here a number of unique historical and technical features associated with these reactors. For example, ZEEP was the first nuclear reactor ever constructed outside the U.S.A. The reactor NRU possessed the world's most intense neutron field for a decade after construction and provided irradiation services and reactor physics data for both Canada and other countries. The organic cooled reactor WR-1 is characterized by such low induced radiation fields that reactor operators may work immediately adjacent to the primary coolant circuit.

1.4 THE CANDU SYSTEM

Nuclear power reactors serve the function of providing thermal energy in the form of steam; this thermal energy is subsequently used to produce electricity by conventional energy exchange processes involving heat exchangers, steam turbines and electro-generators. A general schematic representation of a nuclear power reactor system is shown in Fig. 1.2. The distinctions between alternative nuclear reactor concepts are, to a large extent, associated with differences in the following:

- (1) nuclear fuel,
- (2) moderator,
- (3) coolant,
- (4) physical arrangement.

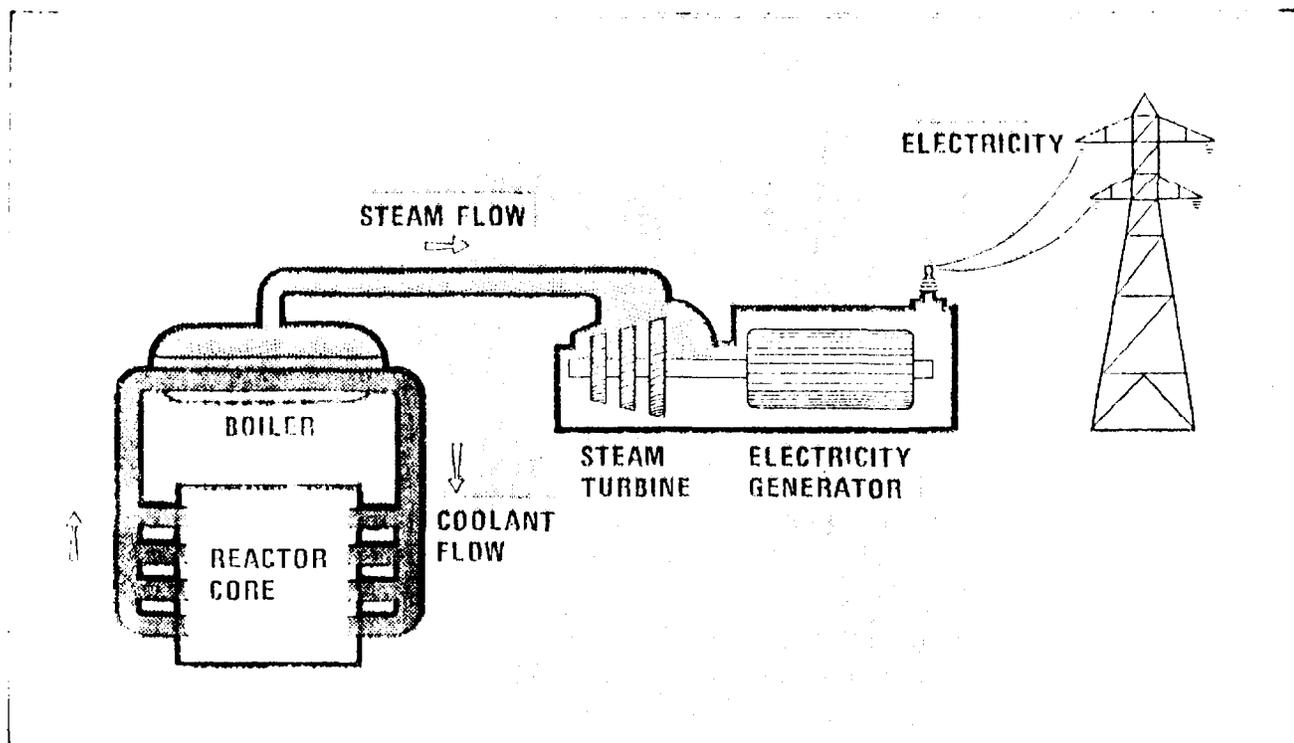


FIG. 1.2: Simplified schematic representation of a nuclear power station.

As indicated in the preceding section, the nuclear fuel in a CANDU reactor consists of natural uranium. Most commonly, uranium is used in a sintered matrix from such as UO_2 and compressed into short cylindrical pellets of about 2 cm in length and 1 cm in diameter. About 25 such pellets are placed inside a thin zircaloy tube to form a fuel pencil some 50 cm in length. Several such pencils are combined into a fuel bundle held in position by structural and plates. Thousands of bundles are required for a nuclear reactor plant.

Depending upon the size of the nuclear reactor, some ten nuclear fuel bundles are placed end-to-end inside a zircaloy pressure tube. The fuel bundles are so placed to provide sufficient space for the flow of a coolant around each fuel pencil. A concentric inert-gas filled space is provided around the pressure tube by a containment tube; this space serves the purpose of minimizing heat transfer flow to the moderator. The space beyond is filled with the moderator.

A varying number of such pressure tube arrangements passing through the axial direction of either a horizontally or vertically located cylindrical calandria form the basic reactor core. The control elements penetrate the calandria at right angles to the pressure tubes. Fig. 1.3 provides a schematic representation of the entire reactor core system.

The use of pressure tubes represents a distinctive feature. It allows for flexibility in the design in that an increase in plant output may be achieved by the addition of more tubes. Another advantage of the pressure tube design is the ability to refuel the reactor under load conditions and so maintain optimum reactivity in the core. Defective fuel elements can be removed from the system without shutdown and without difficulty, thus minimizing the dispersal of radioactive products in the primary circuit while at full power.

With the above basic material composition and physical arrangement for the reactor core, it is now possible to introduce several additional variations with respect to the choice of coolant. The materials for the coolant can be chosen to be light-water, heavy-water or an organic fluid. Each of these coolants require changes in the overall system design configuration in order that design and operating features can be more fully exploited. This is illustrated in Fig. 1.4 where we show these variations as developed to date for the CANDU system.

The above design features have emerged as a result of extensive studies involving the test and research reactors and have been further refined in the course of nuclear power plant construction and operation. The genealogy of various CANDU reactors and the flow of design and operating experience is graphically illustrated in Fig. 1.5.

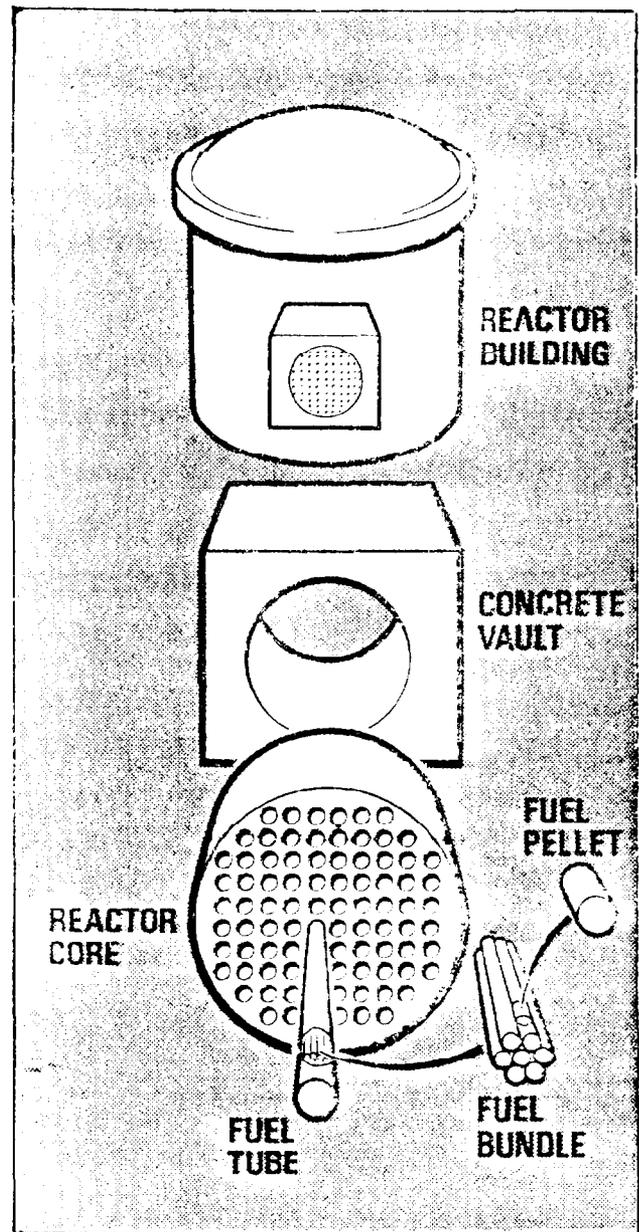
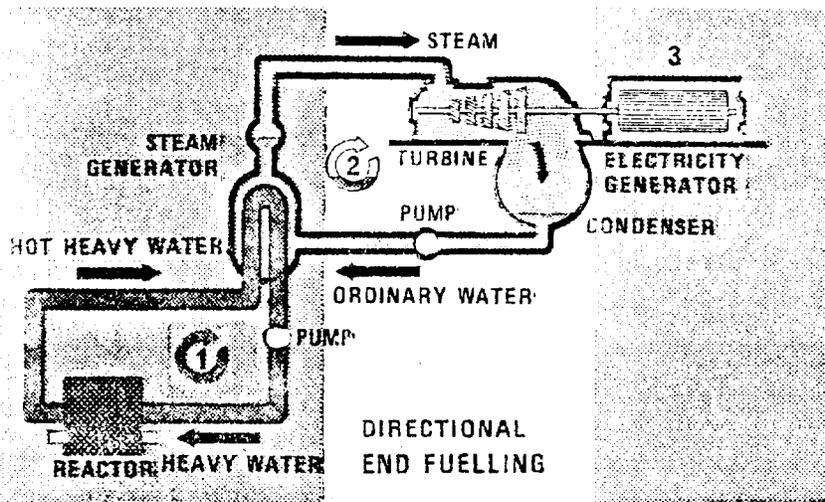
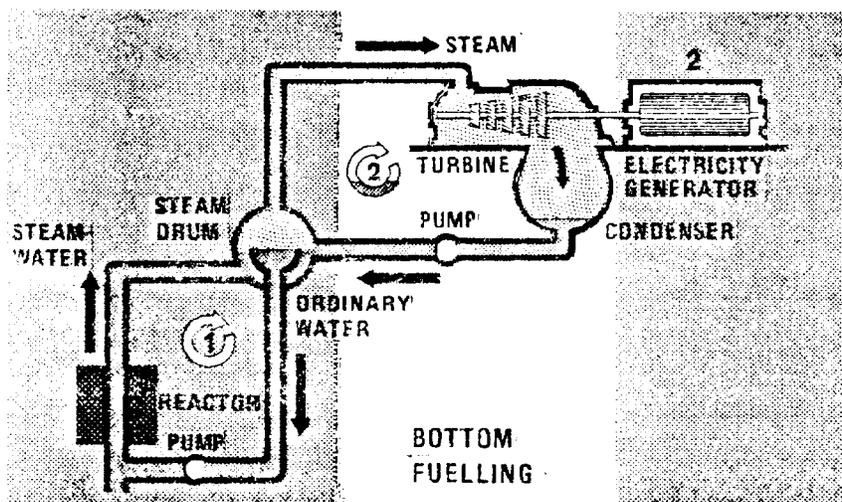


FIG. 1.3: Simplified representation of several components associated with a reactor core and its containment system.

PHW
PRESSURIZED
HEAVY WATER
REACTOR



BLW
BOILING
LIGHT WATER
REACTOR



OCR
ORGANIC
COOLED
REACTOR

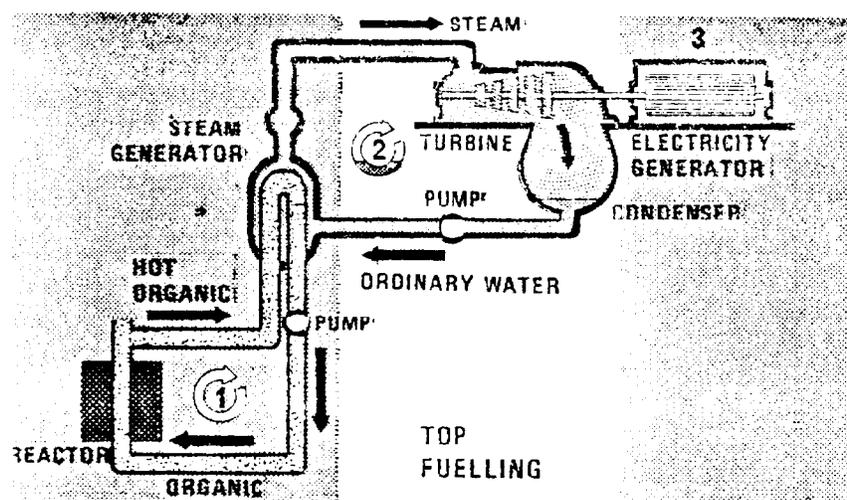


FIG. 1.4: Variations on the basic CANDU system. Note that the important changes occur in the core and heat exchangers but not in the turbine and generators.

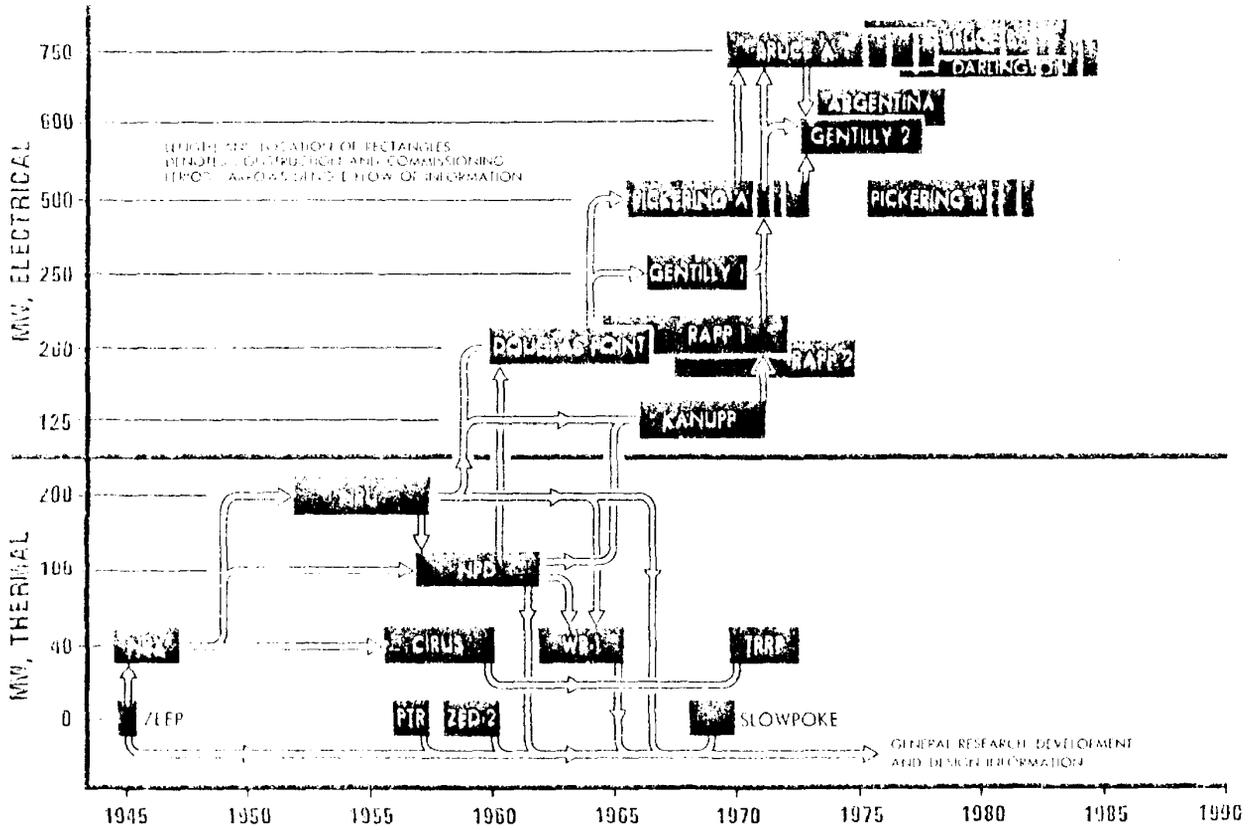


FIG. 1.5: Geneology of the CANDU family of reactors. The length and location of rectangles denotes construction and commissioning. Arrows indicate flow of information.