ATOMIC ENERGY OF CANADA LIMITED
Power Projects

NUCLEAR POWER SYMPOSIUM

LECTURE NO. 1: INTRODUCTION

by

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To introduce this series of lectures, I shall first review a few fundamentals and then launch into a description of the Canadian Nuclear Power Program.

1. FUNDAMENTALS

1.1 Atom

The atom consists of a nucleus surrounded by electrons. The nucleus makes up most of the mass of the atom and consists of two kinds of small particles known as protons and neutrons. The mass of the neutron is approximately equal to that of the proton. The mass of the electron is very much less.

The first figure shows the hydrogen atom. The protons are indicated by a positive sign and the neutrons have been blackened in. The electrons are shown with a negative sign.

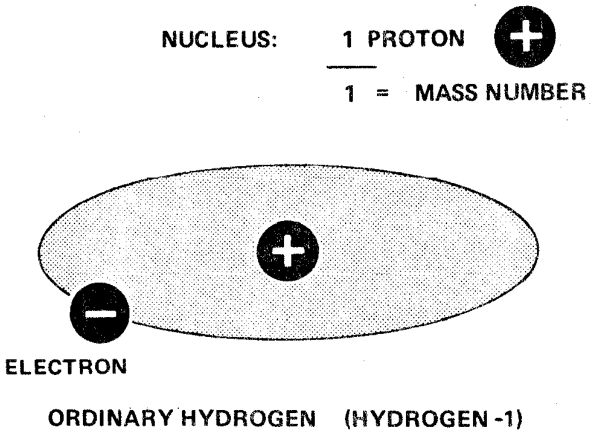


Figure 1 Hydrogen Atom

It should be noted that the atom as a whole has no net charge. The negative charge(s) of the electron(s) is balanced by corresponding positive proton charge(s). The neutron, as its name implies, has mass but no electrical charge. Please note that the diagram is not to scale as the electron orbit may be 10,000 times larger than the nucleus. To give you an idea of size, imagine the nucleus to be the diameter of a baseball; then the electrons would be specks 2,000 feet away.

1.2 Isotopes

Most elements in nature exist in more than one form, being different in the number of neutrons contained in the nucleus. These species of an element are called isotopes. They have the same number of protons and electrons and hence have the same chemical properties (i.e., it should be noted that the arrangement and number of electrons control the chemistry). However, the nucleus properties of isotopes are sometimes markedly different.

The second figure illustrates the different isotopes of natural uranium. Note that uranium consists mainly of U-238 with very small percentages of U-234 and U-235. Only U-235 is capable of fission to any great extent.

Another important isotope, this time of hydrogen, is heavy hydrogen (also called deuterium), and this is shown in Figure 3.

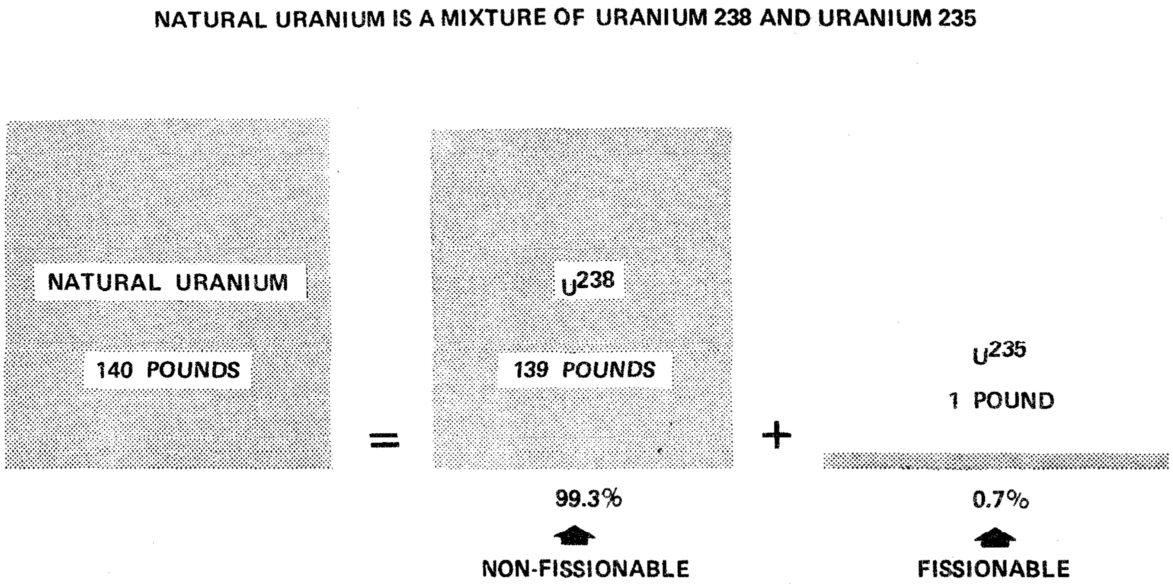


Figure 2 Natural Uranium

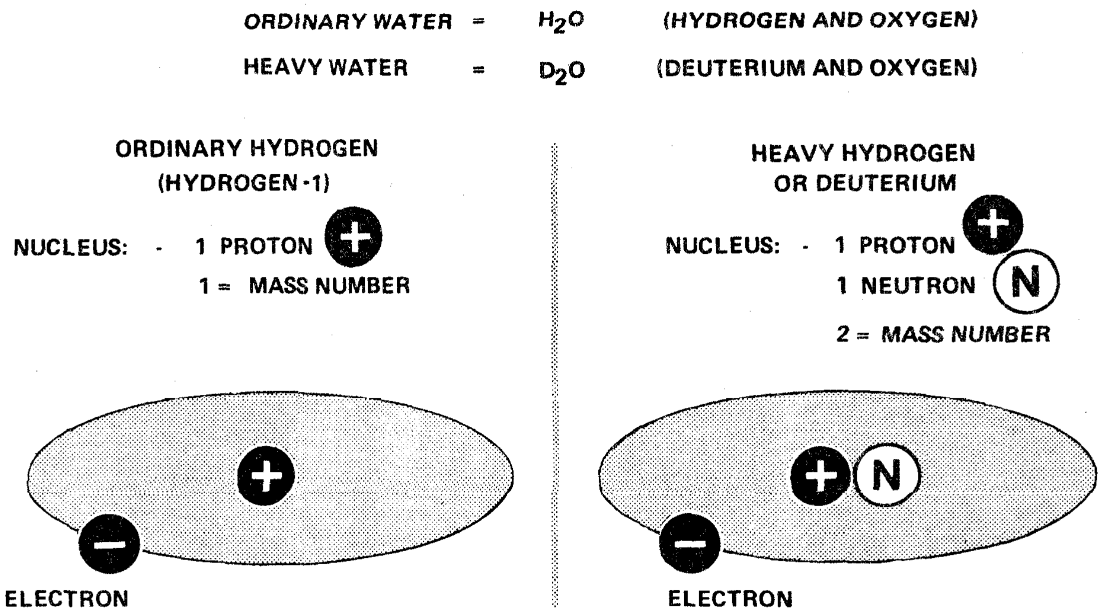


Figure 3 Heavy Water

1.3 Fission Process

The entire atomic energy enterprise rests ultimately on one basic reaction - the splitting of the U-235 atom. In order for the atom to split, a neutron is required to collide with it (as shown in Figure 4). The collision makes the atom so unstable that it cracks almost instantly into two parts, or fission products. These fission products are actually lighter elements in the middle of the periodic table. Some examples of fission products are zinc, bromine, arsenic, krypton, strontium, zirconium, molybdenum, silver, tin, indium and barium. This is, in modern form, true alchemy.

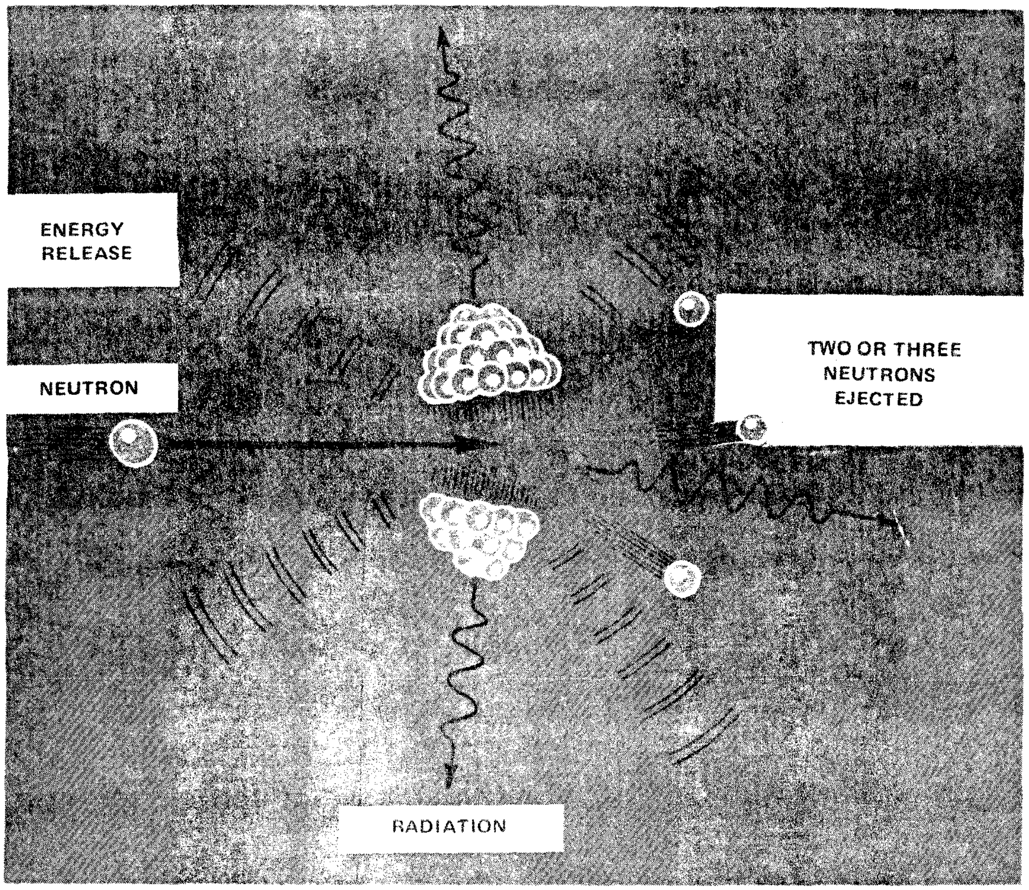


Figure 4 Neutron Colliding With Atom

The two most important consequences of the fission process are:

(i) the production of more neutrons,
(ii) the release of large amounts of heat energy.

On the average, 2.5 neutrons are produced for each fission, but in any one particular case, one, two or three neutrons are produced. If these neutrons are able to split other U-235 atoms, which in turn give off neutrons, then a chain reaction is created. For application in a nuclear reactor, the chain must be self-sustaining and must not die out. If one neutron from each fission were able to cause another fission, then we would have a steady chain reaction. The remaining 1.5 neutrons per fission could be lost for various reasons and therefore not available to cause further fission.

Neutrons can be lost by physically escaping from the reactor. We call this leakage. They can also be lost by being absorbed or captured by other materials within the core that are not fissionable. Therefore, all structural materials in the reactor must be kept to a minimum as they will absorb or capture neutrons that could otherwise be usefully used for fission.

The fission process is remarkable for the amount of heat energy released. A useful fact to remember is that the energy produced by the fissioning of one pound of U-235 is approximately equivalent to the burning of 2.8 million pounds of coal, or 300,000 gallons of fuel oil.

The discussion up to this point has been limited to the uranium-235 isotope. Other materials which are fissionable are Pu-239 and U-233. These two isotopes, however, do not occur in nature but they can be produced by suitable nuclear reactions from U-238 and Th-232.

1.4 Moderator

The neutrons that are produced by the fission process come off at a very high velocity. At these high speeds, the probability of colliding with a U-235 atom and causing fission is very small. Hence, we use a material called a moderator to slow down the neutrons so that they will have a better chance of causing fission.

Figure 5 shows the moderator slowing down the neutrons by a series of collisions. The material used as a moderator:

(1) must not absorb many neutrons, as they are required to collide ultimately with U-235 to cause further fission;

(2) must be light in mass so that a very few collisions are required to slow the neutrons down to the required velocity;

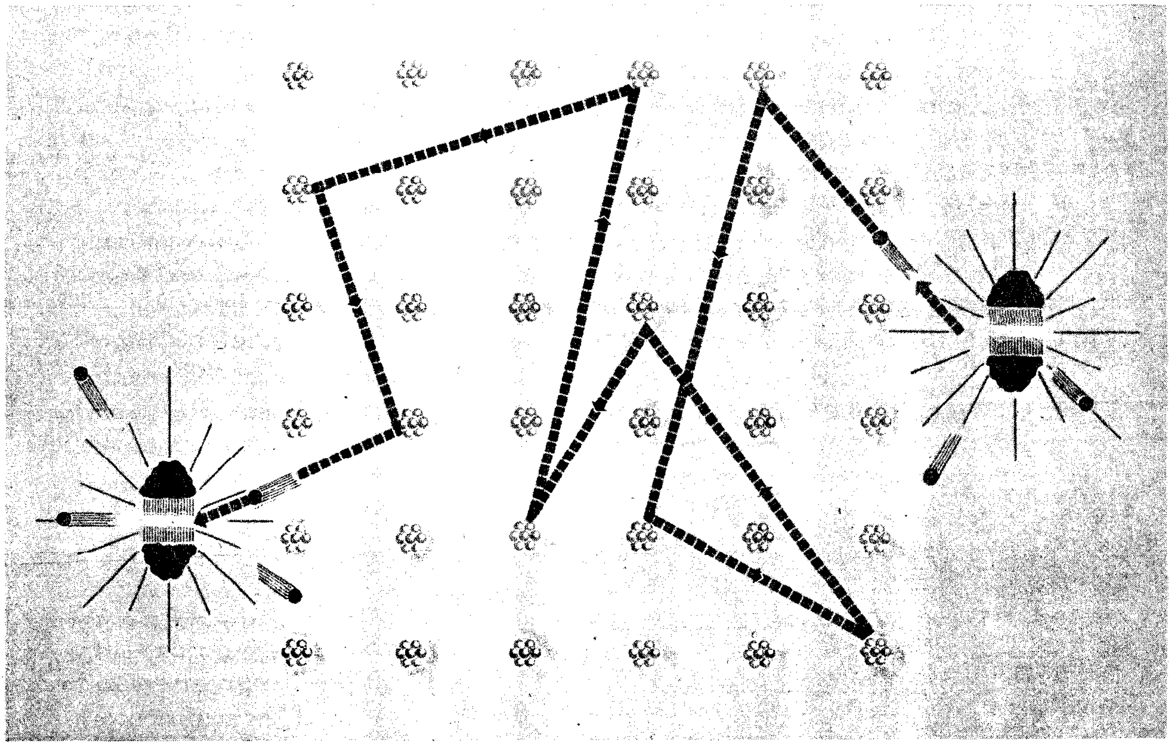


Figure 5 Fission

(3) must have a high probability of collision with a neutron.

Now there are a number of materials which have these characteristics to varying degrees. Their overall performance as moderators can be stated numerically by their "moderating ratio". This is a calculated value which takes into account the relevant characteristics.

Some common moderating materials and their moderating ratios are shown in Figure 6.

MODERATOR	MODERATING RATIO
LIGHT WATER	62
GRAPHITE (CARBON)	165
HEAVY WATER	5000

Figure 6 Moderating Materials

In Canada, we take advantage of the exceptionally high moderating ratio of heavy water. The United Kingdom uses graphite; the U.S.A. and the U.S.S.R. favour light water.

1.5 Nuclear Reactor

Figure 7 is a schematic of a nuclear power station. The major difference from a conventional fossil-fuelled fired plant is that the energy for producing steam is supplied by the splitting of atoms rather than the combustion of coal or oil.

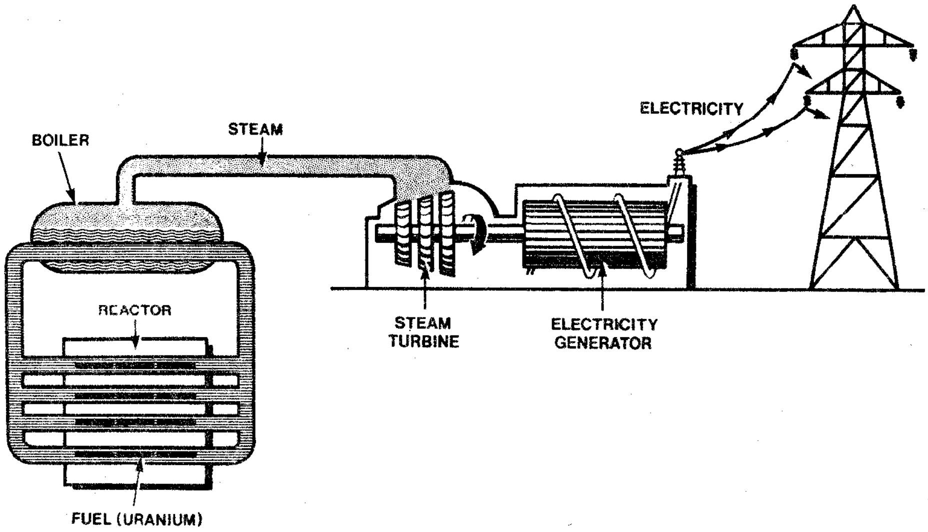
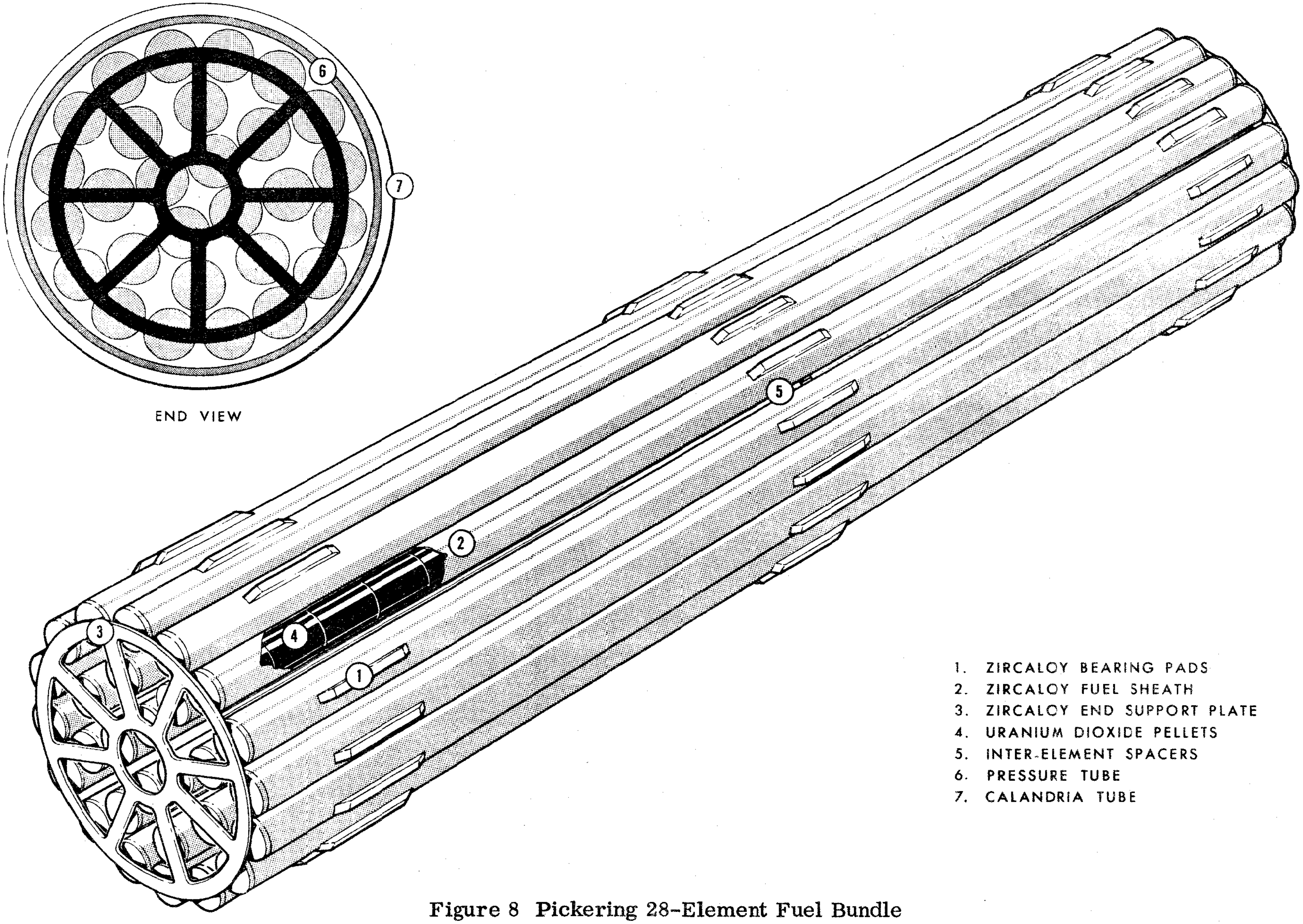


Figure 7 Nuclear Power Station Schematic

The calandria or reactor vessel is a cylindrical tank laid on its side with its end faces forming vertical planes. This tank is filled with the heavy water moderator. Several hundred tubes (called pressure tubes) penetrate the tank and contain the uranium fuel. Four tubes are shown on the figure and they are connected together at each end of the reactor. A fluid, called a coolant, is pumped past the uranium fuel within the pressure tubes, and the heat of fission is transferred to the coolant. The coolant flows on to the boiler where it gives up its heat to produce steam. Some common coolants are light water, heavy water, carbon dioxide, helium, and organics. We use heavy water in our main line of nuclear reactors, and we are experimenting with light water and organics. The heavy water coolant in our reactors is at a maximum pressure of about 1400 psi and a maximum temperature of 570°F.

Figure 8 shows a Pickering fuel bundle. The uranium is in the form of UO_2 and is encased in zirconium alloy tubes (called fuel sheaths) to form elements. Each element is about .6 inches in diameter and $19\frac{1}{2}$ inches long. A number of elements are assembled to make up a fuel bundle. The overall diameter of the bundle is about 4 inches; 12 bundles are placed end-to-end within a Pickering pressure tube.

Figure 9 shows the positioning of fuel bundles within the pressure tube, and the pressure tubes within the calandria.



1. ZIRCALOY BEARING PADS
2. ZIRCALOY FUEL SHEATH
3. ZIRCALOY END SUPPORT PLATE
4. URANIUM DIOXIDE PELLETS
5. INTER-ELEMENT SPACERS
6. PRESSURE TUBE
7. CALANDRIA TUBE

Figure 8 Pickering 28-Element Fuel Bundle

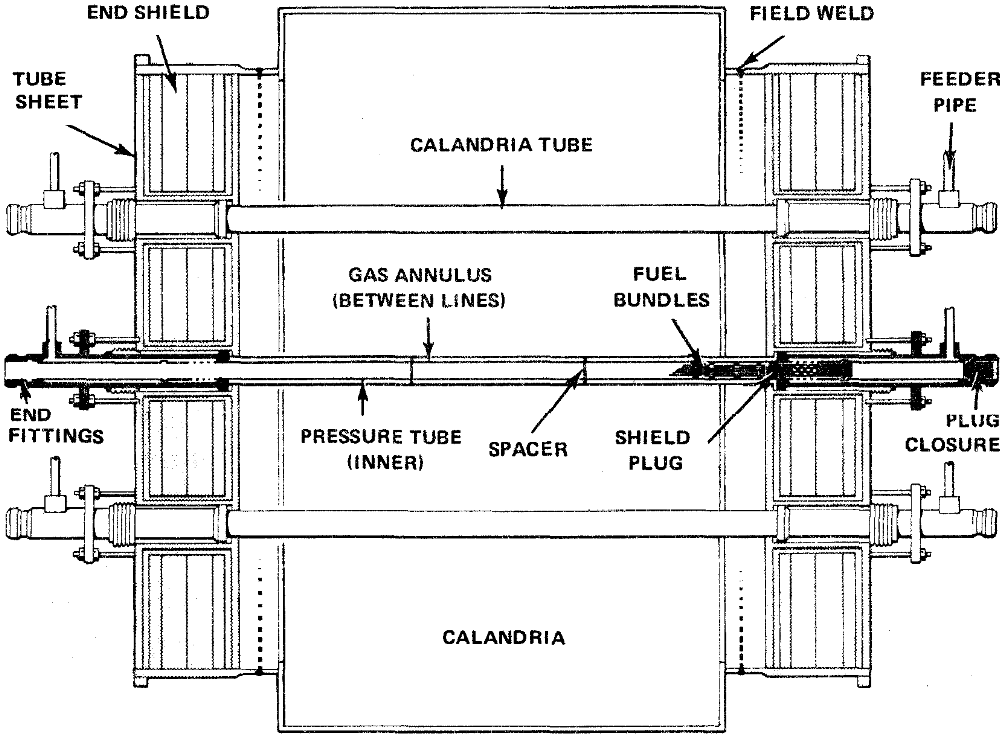


Figure 9 Pickering Reactor Core Schematic

2. NUCLEAR POWER PROGRAMS

To place the Canadian program in perspective, one should examine the historical origins of other national nuclear programs. In this way, we can obtain a much better understanding of why our program is the way it is.

2.1 United States

The United States program evolved from the Manhattan project where the gaseous diffusion process for uranium enrichment was developed. The ten years following the war were characterized by the building of a great many experimental reactors of different types, using various combinations of moderators and coolants. There was a common bond in that all these reactors used enriched fuel, but it is interesting to note that in those early days the light water reactor (LWR) was not considered a front-runner.

Then came the development of a light water reactor for submarine propulsion. This provided a massive technological base for bringing that type of reactor into prominence for civil use. In the years that followed, interest in other potentially attractive systems began to weaken in the face of increasing technological competence with light water reactors, and today LWR's dominate the world scene.

2.2 United Kingdom

In Britain, the nuclear effort after the Second World War was principally in research directed to military needs. At the same time, the energy crisis facing Britain focused early attention on nuclear power.

In 1953, the Calder Hall design was begun and this first full-scale nuclear power plant in the world came into operation in 1956. At that time, Britain made the choice of proceeding with natural uranium and graphite, and it was on this basis, using gas as a coolant, that Britain's nuclear power program was launched. The subsequent availability of enriched uranium has brought forward the Advanced Gas Reactor. This system has had considerable difficulty and will probably be discontinued. It appears that the U.K. is about to make a decision whether to build heavy water moderated reactors or American light water reactors.

2.3 France

In France, the gas cooled, graphite moderated reactor was the main line of reactor development, but this phase of their program seems to have been terminated and they are turning to the light water reactors of U.S. design to help fill the gap until the breeder reactors become commercially available. If the breeders are delayed or if the supply of enriched fuel becomes a problem, the French are keeping the heavy water reactor as an alternative.

2.4 Canada

The Canadian program again had its origin in the Second World War when Canada was assigned the task of developing the heavy water moderated reactor system as a method of plutonium production. This program, but with a decreasing involvement with plutonium, has been pursued steadily since the early 1940's, making Canada the centre of world scientific knowledge and technology in heavy water moderated reactors.

It was natural in the early 1950's when a prototype power station was being considered in Canada that the heavy water systems should be considered first. The system chosen exploited the merits of heavy water as a moderating material; the use of pressure tubes in place of pressure vessels for the primary coolant matched the national manufacturing capability; and the use of natural uranium as fuel allowed the direct use of our national resources of uranium. These conditions led to the commitment to build a small prototype station - the Nuclear Power Demonstration. While the construction of this station was going ahead, studies were being pursued by a joint design team including staff from AECL, the major utilities and industrial groups, to determine the direction of the major steps which it was clearly seen would have to be taken in establishing a national nuclear power program. At the time we made the decision to recommend a heavy water moderated and cooled power reactor, we had available to us the United States Atomic Energy Commission estimates of costs from the enriched light water reactors. Their estimates indicated that the enriched systems could be built for less than the natural uranium fuelled systems but the fuel cost would be two or three times as much. This general picture still holds and, even at today's higher interest rates, we are satisfied that the CANDU system unit energy costs are quite competitive, particularly in a publicly-owned utility system.

Canada has paid a comparatively small price for her national nuclear program. The comparison made in Figure 10 of nuclear program expenditures is based on an estimate which eliminates all expenditures for military uses so far as can be determined from published figures and also allows for the disparity in cost of manpower in Europe as compared with America. We do not claim absolute accuracy in the figures; it is our best effort to make a valid comparison. One should probably not try to draw too many conclusions from the table, except that we feel that from the point of view of manpower effort and funding, Canada has done quite well in a comparative sense.

	MANPOWER 1967	TOTAL COST OF PROGRAM TO DATE
CANADA	1	1
UNITED STATES	9 - 13	16 - 18
UNITED KINGDOM	5 - 7	3 - 3.5
FRANCE	7 - 10	3 - 4

Figure 10 Nuclear Program Comparison of Expenditures

It has been said, however, that one often pays dearly for frugality and what is of much more significance is what we and other countries have gained from our expenditures in the field of atomic energy. There is no doubt that nuclear power is necessary if the needs of the electric utilities throughout the world for increasing energy are to be met. Have we produced a viable system for the present day and one which is capable of further development? We believe we have.

The magnitude of Canada's contribution can be appreciated by the fact that Ontario Hydro's Pickering station has produced more electrical power than any other nuclear station in the world. Pickering will eventually produce a total output of 2,160,000 kilowatts when its fourth and final unit comes into operation in 1973.

The first 540,000 kilowatt unit at Pickering produced its first electricity on April 4, 1971, and reached its full power output only thirteen and one-half weeks after first reactor startup. In starting up the second unit, even this exceptional record was beaten. The time between reactor startup and full power for Unit 2 was seven and one-half weeks. Unit 3 did better yet - from first reactor startup to full power in two and one-half weeks! Other commissioning highlights are given in Figure 11. All three Pickering units have proved to be extremely reliable (Figure 12) and what few problems have been encountered are mainly confined to conventional parts of the station. Particularly encouraging has been the fact that heavy water losses for all units have consistently been below the design target (Figure 13).

	UNIT 1		UNIT 2		UNIT 3	
	DATE	WKS	DATE	WKS	DATE	WKS
CRITICALITY	25 FEB 71	0	15 SEP 71	0	24 APR 72	0
FIRST STEAM	16 MAR 71	2.5	29 SEP 71	2	29 APR 72	0.5
FIRST ELECTRICITY	4 APR 71	5.5	6 OCT 71	3	3 MAY 72	1.5
FULL POWER	30 MAY 71	13.5	7 NOV 71	7.5	12 MAY 72	2.5
IN-SERVICE	29 JUL 71	22	30 DEC 71	15	1 JUN 72	5.5

Figure 11 Pickering Commissioning Highlights

This remarkable record, of course, is no instant success. Pickering stands firmly in the genealogy of CANDU reactors with the operating experience of both the Nuclear Power Demonstration and the Douglas Point Station behind it.

Douglas Point, the first full-scale prototype of the CANDU system, was brought into first operation in 1967 and, while little operational data was available for feeding into the design of Pickering, much had been learned from the operation of Nuclear Power Demonstration and the design of Douglas Point.

The 200,000 kilowatt Douglas Point Nuclear Power Station continues to make a valuable contribution to the electricity requirements of Ontario. With the initial difficulties behind it, the unit has settled down over the past year to routine operation at full power.
One of the most significant facts to be verified by the operation of Douglas Point has been the performance of fuel. Less than 1% of the fuel bundles loaded into the Douglas Point reactor have failed and even these failures have not occurred until the bundles have achieved more than 70% of the design burnup. The direct effect of the failures on fuel costs has, therefore, been insignificant.
Other valuable lessons in the design and operation of a large CANDU pressurized heavy water reactor have included methods for control of radioactivity in the primary system (a condition existing in all water reactors), in heavy water management, and in fuel management.
The design of the three million kilowatt Bruce Generating Station, which is now well advanced, reflects many of the lessons learned at Douglas Point.

It would certainly then be true to say that the CANDU PHW in its present form appears to be a type which will carry the program at least into the 1980's. This type of reactor offers more efficient utilization of uranium resources than the other reactor types. The energy available from a given amount of uranium used in a heavy water moderated CANDU is about double that available from the light water reactor.

While the success of the proven CANDU PHW type makes it likely that this will be developed as far as possible, AECL is not abandoning the quest for both alternative fuels and alternative coolants. At Gentilly in Quebec, a 250,000 kilowatt power reactor has been operating using ordinary boiling water as a coolant, with natural uranium as the fuel. First electrical power at this station was produced early in 1971 and a three-week demonstration run at 100% power was achieved this spring. While this variant offers advantages, both in connection with capital costs and with the elimination of heavy water losses from the primary system, it has always been recognized that control problems inherent in the system would have to be overcome. Considerable work in this direction has already been done and valuable experience gained. As the station acquires more operating experience,

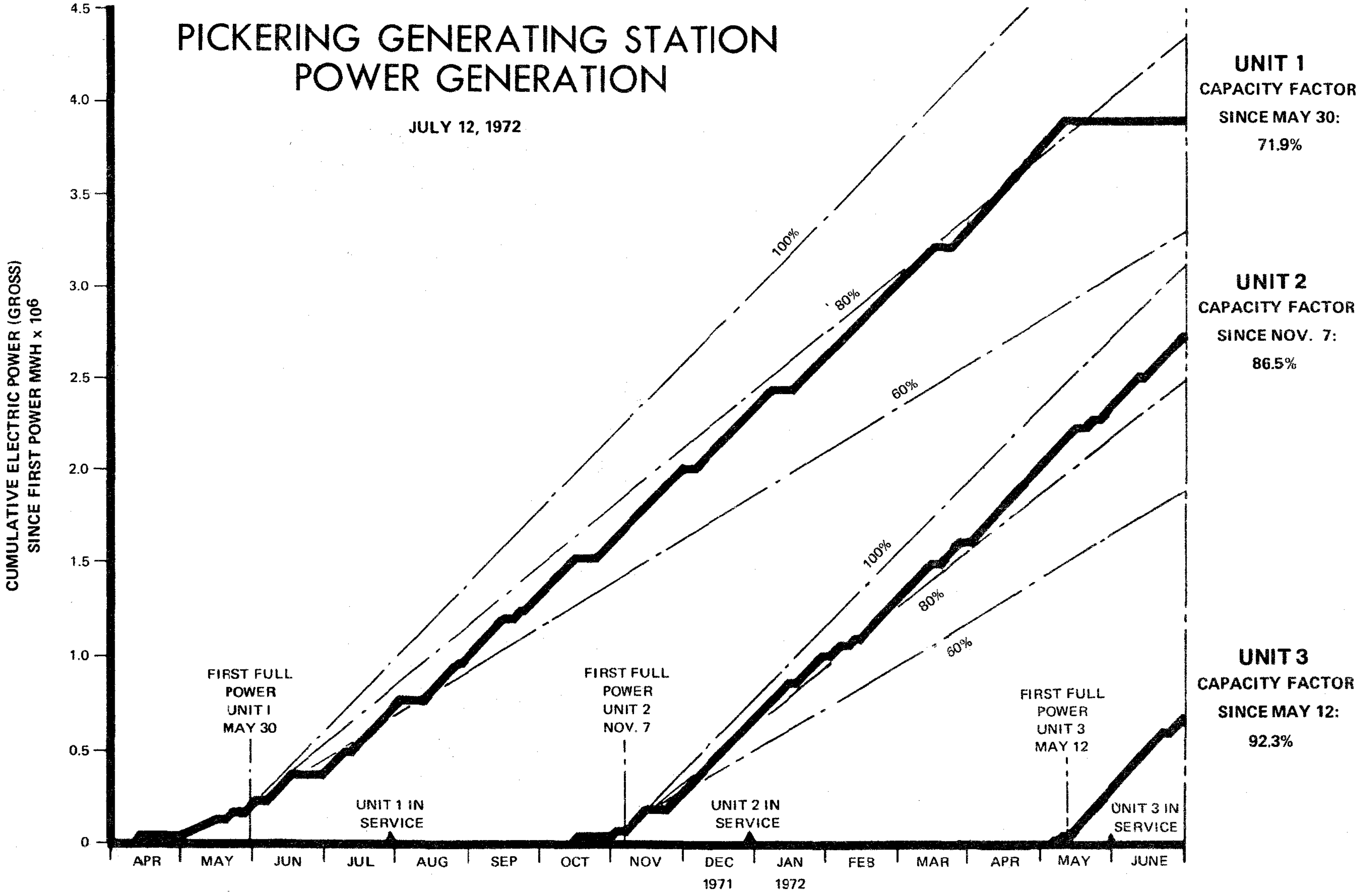


Figure 12 Pickering Reliability

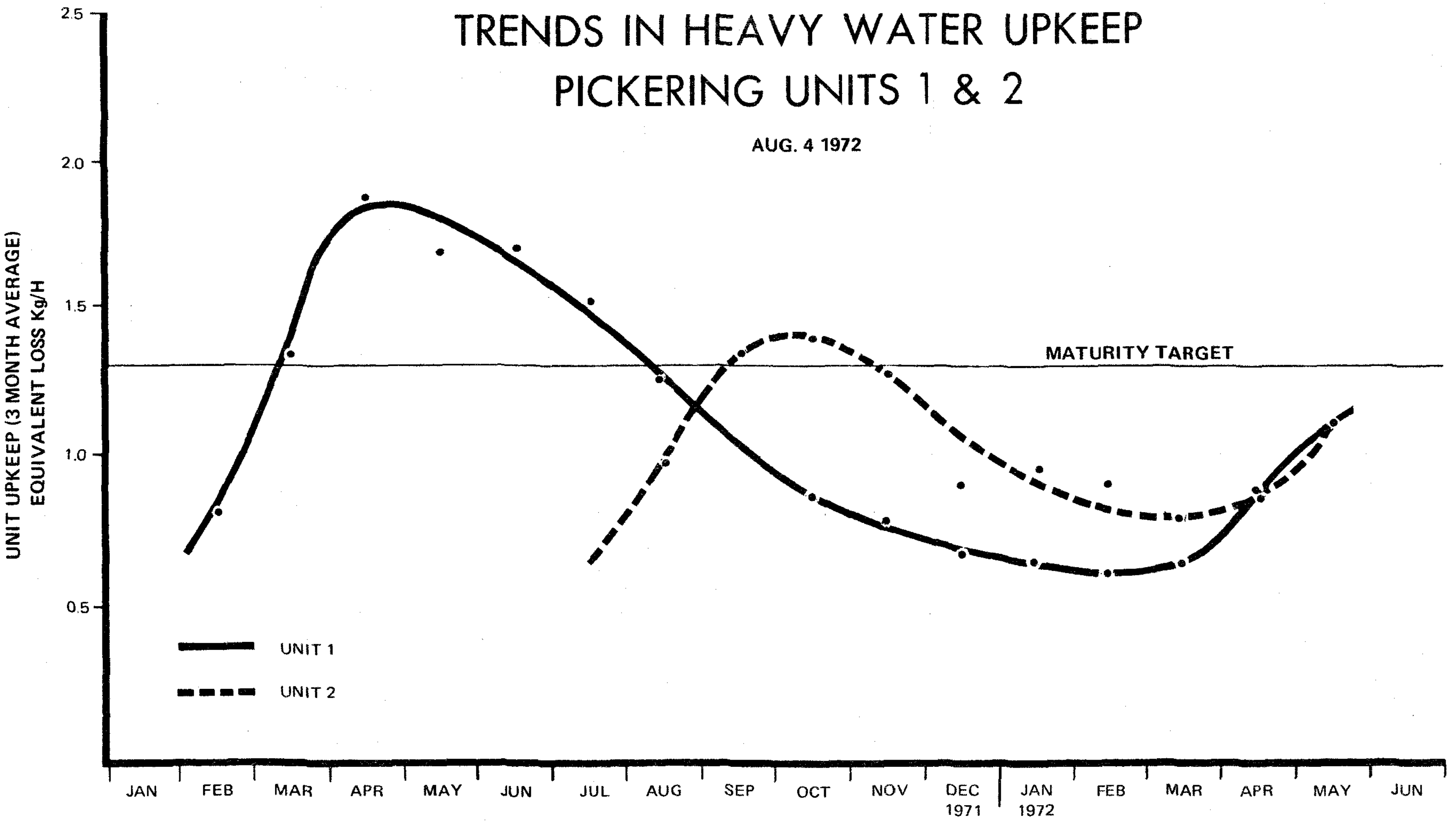


Figure 13 Pickering Heavy Water Losses

more indications will be available of the place which this type of reactor has in the program.

Studies are also underway for a full-scale CANDU power reactor based on the use of organic coolants. The WR-1, a 40 MW thermal reactor at Whiteshell, Manitoba, has been in operation for a number of years and this prototype has proved that organic coolants offer a number of attractions. The use of an organic coolant offers higher station efficiencies, possibly lower capital costs, and very low activity levels around process equipment. It is possible also that, as well as an alternative coolant, an alternative fuel such as uranium metal could result in further economies.

In natural uranium fuelled reactors, there is a valuable by-product formed in the fuel. It is plutonium, a metal which, like U-235, is fissile, and when extracted from spent fuel can be used to enrich natural uranium fuel. By 1981, our fissile plutonium inventory in discharged fuel from Douglas Point, Pickering and Bruce reactors will be about 8600 kg, and the annual production rate will be about 1600 kg/year. This plutonium can be recycled in existing CANDU plants (which have been optimized for natural UO_2) to further improve the low fuelling costs. However, the plutonium can be better utilized by building plants optimized for its use.

For the BLW - with Pu recycle - it is possible to reduce the capital cost and the unit energy cost. Our reactor development program at Chalk River is, therefore, aimed at recycling plutonium in BLW reactors. No additional prototype reactor is required for demonstration or to prove out the technology of this system. The prototype BLW plant at Gentilly and the facilities in our laboratories will be sufficient.

To conclude, we developed the heavy water nuclear power reactor system because, in the mid-1950's, when a decision was needed to start a power reactor program, we were convinced that it would be the most economically viable system in the context of our utilities and best suited to Canadian industrial competence and national fuel resources. Based on experience accumulated since that time, we are still of the same view: we now have a program and a product that rank with the best. We see some very real opportunities to develop the CANDU system still further and to keep it competitive well into the years ahead.