Development Of The CANDU Reactor

Luncheon Address to the Fifth International Conference on CANDU Fuel

Mr. Chairman, Ladies and Gentlemen, former colleagues, new friends and particularly the international visitors. It is a great pleasure for me to speak to you today on The Technical History of the CANDU Reactor.I will highlight some of the achievements in the development of CANDU, taken from the new book "Canada Enters The Nuclear Age", published in 1997 by McGill/Queens University Press, which describes 40 years of R&D at AECL.

The history of such a tremendous achievement as the CANDU reactor is a personal feeling; everyone associated with any part of this project would have their own version of a history---and what are the most important points that should be discussed. I know that in the preparation of Canada Enters The Nuclear Age there was extensive information included in the early drafts that had to be deleted because of lack of space--not because it wasn't important--much to the consternation of the authors. But editing had to be done--and in retrospect the decisions to delete were correct.

The CANDU reactor is one of Canada's greatest scientific/engineering achievements, that started in the 1940s and bore fruit with the reactors of the 60s, 70s, and 80s. Remember though, nuclear science was not new to Canada. About 100 years ago Sir Ernest Rutherford made some of his key discoveries while working as a professor at McGill University in Montreal; for example he showed that radioactivity is, in many cases, a manifestation of the long-sought-after transmutation of elements. Many Canadian scientists studied under Rutherford, giving Canada a solid nuclear base. After Rutherford returned to England, nuclear research continued in Canada, mainly at Queens and Dalhousie Universities. Also the work of G. C. Laurence at the NRC, the discovery of uranium at Great Bear Lake in 1930, and the setting up of a plant to extract the radium and later the uranium from the Great Bear Lake ore gave Canada status as a Nuclear Nation.

In the 1930s work in Italy, France and Germany culminated in the demonstration of nuclear fission early in 1939. Its potential in both peace and war was widely recognized. The French group at the College de France, led by Fredrick Joliot-Curie included Hans von Halban, an Austrin, and Lew Kowarski, a Russian. Amongst their discoveries this group found that at least two neutrons are emitted when a fission occurs. But before a chain reaction can be considered these neutrons must be slowed down; i.e. moderated. And this group knew that heavy water would be a very efficient moderator.

Joliot-Curie obtained permission to purchase the world's supply of heavy water from Norway [in fact the Norwegian Company provided it on loan]. By this time [1940] the 2nd World War was on, and Germany also had an interest in the D2O. The French agent laid a false trail which misled the German Air Force into intercepting the wrong flight and forcing it to land at Hamburg, while the heavy water reached France via Scotland.

The group at the College de France were performing neutron diffusion experiments in D2O when the Germans broke through the Netherlands and Belgium into France. The Earl of Suffolk, British scientific attache in Paris, arranged for the escape of about 150 scientists/engineers and technical personnel from France to Britain. Joliot-Curie did not go, but in 1940 Halban and Kowarski sailed from Bordeaux in a small ship with the 185.5 kg of heavy water.

Pause for a few seconds to think what might have evolved if the Germans had intercepted the heavy water during its journey from Norway to France, or from Paris to Britain.

These 150 people joined other staff from Britain and around the world at the Cavendish Labs at Cambridge where many experiments were done: one of these showed that a mixture of uranium and D2O could sustain a chain reaction. A monumental discovery, particularly for the future CANDU Reactor.

The entry of the USA into the war changed the tempo of nuclear development. Military needs demanded utmost secrecy and security, and relations became strained between the USA and the European team. Negotiations to relocate the European team were started, and ended with an agreement between Britain and Canada, with the support of the USA, to move the British heavy water project from Cambridge to Montreal, in 1942. This was the start of D2O moderated reactor research in Canada. In 1943/44 the labs were moved from Montreal to the newly established laboratory at the "remote" location of Chalk River, Ontario.

Professor John Cockroft was appointed Head of the Montreal Labs and moved to be Head of the Chalk River labs for one year. It was decided to build a research reactor, and when finished NRX become the backbone of the experimental programs. However, NRX was a very complicated enterprise and took a long time to design and build; so a very simple reactor ZEEP [zero energy experimental pile] was built and went critical on 5 September, 1945. It was the first reactor to go critical outside the USA, and for years was a useful facility for basic lattice experiments. The construction of NRX continued and it went critical on the 22nd of July, 1947. For several years it was the most powerful research reactor in the world, as was NRU in the 50s to 80s

In 1947 W. B. Lewis was brought from the UK, where he had been a key participant in radar development, to head Chalk River's R&D program. He became the main driving force for CANDU over the next 25 years. J. L. Gray was on the administrative side of the labs, and later became President of AECL. Prime Minister W. L. MacKenzie King had appointed C. D. Howe as Minister of the Department of Munitions and Supply and other posts. Howe was a powerful person who kept up to date on three important aspects of nuclear matters: uranium supply, nuclear research and development, and nuclear regulation and control. He was a former professor of engineering and understood nuclear fission and the potential power of the atom; he and J. L. Gray became strong allies, and nuclear plans flourished.

On 1 April 1952 the Government of Canada formed Atomic Energy of Canada, Limited, a Crown Company reporting to Cabinet through a Minister. Other important Organizational events were the formation of the Atomic Energy Control Board in 1946 and the declaration of the Atomic Energy Act in 1954.

By the early 50s development of the last major hydro-electric sites on the Niagara, Ottawa, and Saint Lawrence rivers had been committed. Dr. Percy Dobson, Head of Research for Ontario Hydro, recognized the need for a new source of power. He got R. L. Hearn, then Chief Engineer and later Chairman of Hydro, interested in the work going on at CRNL. In 1953 the AECL Board of Directors agreed to set up a study team [the Nuclear Power Group--NPG] to look at the possibilities of a small power reactor. H. A. Smith of Ontario Hydro was appointed head of the team. Members were from Ontario Hydro, Brazilian Traction, Shawinigan Chemicals, Babcock Wilcox, Montreal Engineering, and B. C. Electric. The formation of this group marked the beginning of Canada's nuclear power program. After months of calculations and discussions the NPG decided that a heavy water moderated, natural uranium reactor was feasible. According to John Foster, if the team had not recommended this, W. B. Lewis would have insisted that another team be formed.

When the Government decided to proceed with a demonstration nuclear power reactor [NPD] AECL invited 7 Canadian corporations to bid on a contract to design and construct the NPD plant. The Board recommended that Canadian General Electric be selected.

Participation by a utility was also essential. Two had presented proposals: Ontario Hydro and Nova Scotia Light and Power. Ontario Hydro was chosen. Think what it would have been like if NSL&P had been chosen---we would be meeting in Halifax, and probably eating lobster for lunch.

While NPD was being designed and built the NPG investigated conceptual designs for much larger reactors. In May 1957 they concluded that the minimum commercial size would be about 200MWe and it should use horizontal pressure tubes to contain the fuel and pressurized heavy water coolant. Part of the reason for the recommendation is that a natural uranium reactor must be larger than an enriched uranium reactor; a pressure vessel would be very large and beyond the current state-of-the-art of construction. A second reason was that a thirty year amortization period was necessary to achieve a low unit energy cost. Because of uncertainties in the design and longevity of in-reactor components it was considered necessary that the core could be replaced; that would be possible with a pressure tube design. Another factor in considering a pressure tube design came from the USA. The General Electric Company had been given a contract to build a reactor which was to operate at power reactor conditions. They chose a pressure tube design, using Zircaloy pressure tubes. The likely availability of such tubes introduced another degree of freedom into the conceptual design for CANDU, and the NPG proposed that future power reactors use horizontal pressure tubes, not a pressure vessel. This led to a major change in the NPD program. The original design was for a vertical pressure vessel and the vessel was being constructed in Scotland. The contract was canceled and a re-design was started. This caused a delay of about two years in the completion of NPD. But the delay was worth it since NPD played an important role in understanding the CANDU system, as a test bed for fuel and pressure tubes, for coolant experiments [including operation with a boiling coolant], in showing that a power reactor could be used to produce Co-60, and in preparing AECL and the utilities for future stations.

Another advantage of the pressure tube design was also recognized; the same basic design could be used as progressively larger units were needed by the utilities---just add a few more pressure tubes, a bigger pump and a higher power turbine. [Sounds simple-eh!]

The original fuel for NPD was to be Zircaloy-clad uranium metal, with some thoughts of developing a high-temperature aluminum alloy as sheathing, because of the high cost of zirconium. However, information from tests by Bettis Atomic Power Labs in the loops of NRX showed the excellent performance of UO2, even with purposely defected sheathing. This sounds straight forward, but in fact there was almost an international incident over this: The head of NRX [Gib James] x-rayed an experimental fuel assembly for the US Nautilus fuel development program that was to be irradiated in the loop in NRX; and contrary to information supplied by the USAEC, found that the the fuel was UO2, not uranium metal. The USAEC claimed that we had breached security, but Gib James told them "no one puts anything in the fuel channels in my reactor without an x-ray examination; we have done it from the start". AECL survived the ensuing investigation and the co-operative program went ahead. W. B. Lewis became convinced that UO2 was a better choice than uranium metal, and at an NPD Technical Committee meeting in October 1955 he told the meeting that the fuel would be UO2.

It is worthwhile to stress the importance of having the loops in NRX and later NRU. The first loop was built by Bettis for their experiments on fuel for the Nautilus submarine. The USAEC finally recognized that some AECL personnel had to be made aware of what the tests were about, and several of us were given "Q" clearances by the US Military. Gradually AECL was allowed to incorporate this information into its own program, particularly the use of UO2 and Zircaloy-2, the alloy for sheathing material. AECL began to build its own loops in NRX and larger sizes in NRU. These were extremely important in doing experiments on fuel, on pressure tubes, on safety, on heat transfer, on in-reactor instrumentation, on coolant flow and vibration, on coolant chemistry, on the formation of deposits [crud], and on the clean-up of radio-activity after fuel had defected.

Another important, but definitely not planned, source of information arose in December, 1952 when NRX had a loss of regulation accident with irrepairable damage to the inner components and extensive coolant leakage. The reactor had to be taken apart, the building cleaned, new equipment built and installed, and the reactor put back together and restarted. It was the first time such a large radio-active structure had had to decontaminated and rebuilt. In retrospect it was a good experience; the information and experience gained was very important to AECL, the Canadian military, the AECB, the USAEC [who sent US military personnel to help in the cleanup-including the future president, Jimmy Carter], and the entire nuclear community. When the leak occurred, and on the basis of a preliminary call from Chalk River, AECL's president told the press there had been a "pinhole leak". When a group of Americans visited Chalk River to discuss the accident one of them began his remarks by saying that Canadians must measure pinholes as they do gallons, because this was certainly an Imperial Pinhole.

In 1959 the Federal Government and Ontario Hydro agreed to commit a program of design, development, construction, and operation of the Douglas Point Station. At this time the Nuclear Power Plant Division was formed; this eventually became AECL CANDU. The NPPD consisted of personnel from AECL, over half a dozen private companies, and attachments from several utilities. Engineers were recruited from the AVRO Arrow project when it was canceled in 1959. The establishment of the NPPD was controversial since a private company, CGE, was already engaged in design and construction of NPD and was actively marketing the concept to possible foreign clients. However the Division was set up to design Douglas Point, and in cooperation with the utilities and private businesses, it combined very successfully to produce designs for this and subsequent reactors.

In the early years of operations Douglas Point was plagued with problems. The main coolant pump had to be modified and valves required frequent maintenance. Repairs were difficult because of lack of space and radiation levels were high, due to lack of attention to proper water chemistry control, which resulted in the formation and subsequent movement of radio-active corrosion products into the steam generators and other out-reactor components. Processes were developed to remove the corrosion products and studies defined the proper water chemistry levels; these were set and rigourously kept.

Early operations showed that many commercially available components were not good enough. This led to the development of special groups within AECL to study the needs and to set up quality assurance programs that would ensure Nuclear Grade products. This was very important for Canadian industry; many objected, but those that accepted the stricter demands were able to continue to supply their products to the CANDU program, and also world wide.

For the next part of this talk lets take a look at a few of the components that required special studies to make them suitable for nuclear use. Firstly there are the standard out-reactor components such as pumps, valves, steam generators, and piping.

Pump Seals---At startup of NPD in 1962 pump seals lasted typically 200 hours. With 25 years of development pump seal life has been extended to five years. These studies involved the interaction of hydrodynamics, vibration, lubrication, flatness of surfaces, clearances, wear, metallurgy, corrosion, and fabrication techniques. The seal problem was augmented as the size of the pumps increased when reactor output was raised: shaft diameters were increased to 200mm, and horsepower increased significantly: 500 hp for NPD compared with 11,000 hp for Bruce. To achieve success four separate areas were studied: seal design, seal material--the original cobalt alloy seal faces were replaced with titanium carbide to lower cobalt release to the coolant---, suppliers' quality control, and maintenance and operating procedures at the power plant. Typical loss of electrical generation due to pump seal problems is less than 0.05% for CANDU reactors. AECL became so efficient in designing seals that they were consulted by NASA after the seal failure on the shuttle program. [the Challenger disaster]

Valves---It is imperative to minimize heavy water leakage and to extend the life of the valve packing. In the early 70s AECL began a program to address these needs. The result was live-load packing. This is a spring-loading technique incorporating sufficient energy storage to compensate for the compression set; [densification of the packing due to compression loads] or wear of the packing in the stuffing box. The original designs lasted for a few tens of cycles, but application of the new technology has increased this to many thousands of cycles and on back-fits of existing valves has reduced leak rates by a factor of 25, and radiation doses to valve maintainers by a factor of 100.

Steam Generators--Steam generator development concentrated on a complex interaction of design, water chemistry, materials, and a series of parameter tests. Some of the important aspects studied include effects of flow rate and erosion, water chemistry, overall and localized corrosion, build-up of debris, temperature and pressure, vibration, weld integrity and internal stresses. The size of the problem---think of the surface area involved in a steam generator; for Pickering about 5.5 acres [excuse the non-metric units]. A hole smaller than 1/16th" diameter in this area is unacceptable. Also think of 7100 tube-to-tube sheet rolled joints, where any crevice can be a place for debris to accumulate, for accelerated corrosion, and for the occurrence of boiling, which can result in tube cracking due to chemicals that concentrate in the boiling water. Tests showed i/

the beneficial effects of adding hydrazine to react with any traces of oxygen [to reduce corrosion] ii/ additions of sodium hydroxide and sodium phosphate to counteract the effects of impurities such as sulphates and chlorides, iii/ additions of an organic amine, which is sufficiently volatile that is does not concentrate in the steam generator, to control alkilinity.

To detect if a leak had occurred in a steam generator tube infrared absorption spectrometry monitors, which were developed at CRNL, were added on-line. If a defect was detected eddy current techniques, also developed at CRNL, were used to determine which tube was leaking and had to be plugged. Another problem that became evident was the accumulation of sludge, which can restrict heat transfer and reduce the efficiency of the system. Methods to eliminate or at least reduce such build-up were studied; none was completely successful and sludge build-up is still a problem

Piping---The engineers felt that stainless steel was not required for the reactor coolant system piping and associated vessels. This certainly was contrary to the conventional wisdom of the nuclear industry at that time. Nevertheless Canada went ahead and specified carbon steel for reactor coolant system use. Carbon steel is lower in cost, immune from intergranular stress corrosion cracking, and is easier to decontaminate than stainless steel. The decision to use this material has proven to be correct in that, to date, no problems have arisen from its use.

Now, lets look at a few of the in-reactor components. For this audience the most important of these is the fuel. At lunch tomorrow you will be getting a full charge of this when Ron Page speaks to you. However I would like to insert here a couple of items.

Early in the UO2 experimental program potentially devastating news came from General Electric's Vallecitos, California Labs. Several of their Zircaloy-sheathed elements had disintegrated during irradiation, and G. E. were contemplating abandoning Zircaloy in favour of stainless steel sheathing for the BWRs. If there was concern about zirconium-based sheathing in the USA it was doubtful if there could be a viable industry to supply only Canadian needs; and stainless steel absorbed too many neutrons to be used with natural uranium fuel in CANDU reactors. AECL had not experienced such disintegration and questions were raised on material impurities. U. S. analyses showed a high concentration of fluoride in the UO2, [probably from residual hexafluoride from the enriching process]. AECL postulated that such concentrations could cause the disintegrations observed, and they launched a definitive test with two levels of fluoride. Within Canadian specifications there was no problem, but with high fluoride concentrations disintegration occurred. This information was quickly made public; Zircaloy was kept as the preferred sheathing for the US reactors. Without this prompt explanation of the problem and easy solution the entire CANDU concept could have been in jeopardy.

And secondly---Initially the determination of fuel burn-up was done by chemical analyses for fission products. This was a long process. Results were not very accurate, and often were quite different from burn-ups estimated from calorimetry and measured values of the neutron flux in the reactor. This meant that calculations of power, fission product production, and percentage of fission product gas release were suspect. The Research Chemistry Branch had built a mass spectrometer. The funds for this were partly justified by the need for more accurate burn-up analyses, by measuring the U-235/U-238 ratio in samples removed from the irradiated specimens; from such data the burn-up can be calculated to a high degree of accuracy. The first few samples were done with great enthusiasm by the research scientists, to prove that their system worked. However, when samples began to be submitted on a frequent basis there was a minor rebellion: "the mass spectrometer was a research instrument, not a service tool for the fuel group, and we are research scientists, not assembly line analysts". Heated discussions followed, but managerial diplomacy prevailed; essential samples would be processed, with the promise that another setup would be obtained to provide the burn-up analyses needed for a full understanding of fuel performance. And this was done.

Fuel Channels---The fuel channel consists of the pressure tube, which contains the fuel and hot primary coolant; the garter springs to keep the pressure tube and calandria tube from touching; the calandria tube, which keeps the cool moderator from contacting the hot pressure tube; and the rolled joints, which connect the pressure tube to the out-reactor circuits. In NPD the calandria and the calandria tubes were made of aluminum, but in the larger reactors more strength and better corrosion resistance was needed; so the tubes were changed to Zircaloy and the calandria to stainless steel. The fuel channel must be neutron-economic, corrosion resistant at the operating temperatures, and have sufficient strength to withstand the pressure of the coolant for short term exposure and for long term creep and sag. Pioneering work by the U. S. Military, under Admiral Rickover, developed Zircaloy-2 for fuel sheathing. This alloy had the corrosion resistance and could give the strength needed for pressure tubes, if some cold work was introduced. The experimental program to develop the pressure tubes was a huge endeavour, involving hundreds of people at AECL, Ontario Hydro, and private industry [especially the tube manufacturers]. Items of interest included alloy composition, strength [including creep and sag], effect of cold work and heat treatments, corrosion, internal stresses, both uniform and localized, effect of manufacturing defects, rolled joints, critical crack length and the leak-before-break concept.

It appeared that the design of the pressure tubes was set, but, on 10 August 1974, a traumatic day in CANDU technology, previous theories had to be re-examined: primary coolant was detected in the annulus gas in Pickering 3. It was a leaking pressure tube. Instruments showed which tube was leaking, and when it was removed examination showed that the leak was in the tube, not the rolled joint. This launched a major investigative program to determine how the leak occurred, why, how many tubes were affected, and what could be done to remedy the problem. The leaks were attributed to what became known as delayed hydride cracking. This was not an isolated incident; 16 other tubes in Pickering 3 developed leaks, and eventually 52 were replaced in Pickering 4. Both reactors had Zr-2.5%Nb tubes; no leaks were detected in the longer exposure but lower tensile strength Zircaloy tubes of Pickering 1 and 2.

An extensive investigative/development program followed to determine the cause of the defects, and how they could be eliminated. The tests showed that zirconium hydrides built up in an an area of the pressure tube that was over-stressed due to the misapplication of the procedure to install the rolled joints. Focus centered on how to eliminate localized stresses, how to reduce the hydride levels, and why did the hydrides concentrate at the over-stressed areas. These topics are still being investigated, including renewed efforts on non-destrucrive testing. Changing the tube material back to Zircaloy was considered---by a narrow margin the decision was to stay with Zr-2.5%Nb, and has stayed firm. DHC also caused the failure of a Zircaloy pressure tube in Pickering-2 where the pressure tube and calandria tubes touched because of an out-of-place garter spring. Hydrogen migrated to the cold spot and hydrided areas formed to cause weak spots which eventually failed. This proved to be a major problem, that involved a great many of the creative minds of AECL and Hydro [plus their consultants]. Systems were devised to determine how many other garter springs were out of place [many] and what were the possibilities of further defects of this origin. The process [SLARette-for search, locate, and replace] is still being successfully pursued by AECL and Ontario Hydro.

There are many more important factors in the story of pressure tubes; these are given by C. E. Ells in Canada Enters The Nuclear Age.

Rolled Joints--What is a rolled joint? No it is not a cigarette of any form; it is where the Zircaloy pressure tube is rolled into grooves machined into the 403 stainless steel end fittings. 403 stainless steel was chosen because it had good corrosion, adequate strength, and an expansion coefficient very close to Zircaloy so that changes in temperature would not put undue stress on the joint. Some people said these would not work, but the designers had faith, and were correct. There have been no failures or leaks attributed to rolled joint defects. The Russians were particularly skeptical, and most Russian visitors questioned this design. It seems they were convinced the rolled joint would not work and they simply would not believe the answers of "good performance, no problems, no defects".

Heavy Water---Heavy water is expensive, and the CANDU reactor needs a lot of it. Therefore programs were put into operation to i/ find the cheapest way to produce it in large quantities, ii/ ensure that components did not leak. iii/ develop instrumentation to detect leaks, and iv/ ensure the reliability of the D2O production plants. As we heard earlier the first significant amount of heavy water was produced in Norway. Canadian production started in 1943 at Consolidated

Mining and Smelting at Trail, BC, under contract to the Manhattan Project. D2O was extracted from a hydrogen stream by a catalyzed vapour-phase exchange reaction between steam and hydrogen. By 1945 about 8 Mg .of D2O was produced. The USA also produced 21 Mg of D2O in their distillation plants. Of this 29 Mg of D2O the USA loaned Canada 20 Mg for ZEEP and NRX. In 1955 an exchange program between The USA and Canada allowed Canada to purchase enough D2O for the initial phases of the CANDU program, and access to all the American process D2O production technology. Between 1955 and 1967 Canada purchased about 1000 Mg of D2O from the USA to satisfy the needs of ZEEP, ZED-2, WR-1, NPD, Douglas Point, and the first Pickering unit.

A Canadian supply was needed and in 1963 AECL sought bids for a D2O plant to provide 900 Mg over a five-year period. The result was the Glace Bay fiasco! Glace Bay was plagued with problems: managerial, labour, financial, design, choice of materials, and organizational. Eventually AECL was called to the rescue, and the plant was extensively revised and began operation ten years later that the original schedule. A second plant was constructed at Port Hawkesbury in Nova Scotia; again problems were encountered which limited production to half the rated capacity. More D2O plants were built at Douglas Point, one by AECL [later purchased by Ontario Hydro] and one by Ontario Hydro [two others were committed by Hydro but never completed]. By the end of 1974 Canadian production began to exceed demand, and has done so ever since.

The development program was wide ranging, including process analysis and control, process chemistry, analytical chemistry, materials behaviour, mechanical equipment, sieve tray hydraulics and efficiency, gamma scanning and water distillation. Hundreds of person-years were spent on this program; for those of you with greater interest I refer you to H. K. Rae's section in Canada Enters The Nuclear Age.

A few words on the fueling machines, and the bi-directional fueling that they allowed. These machines are incredibly complicated, having to latch onto the pressure tube while the coolant is at temperature and pressure, and where any spilt D2O is unacceptable. They have to allow movement of the new fuel bundles into the channel, and more importantly ensure that the spent fuel is not mishandled on discharge. Also they have to ensure that the bundles are not subjected to abnormal stresses during loading or discharge, for example by uneven coolant flow, by being caught in the latches that make the seal, or by impact where one bundle is rammed into another. On-power fueling had been shown to be feasible at NRU; the technology was expanded to provide a system that has worked well for CANDU stations, with very little loss of electric capacity due to fueling machine outages. The bi-directional fueling with the 50 cm long bundles gives about twice the burn-up over uni-directional fueling with full length fuel bundles, and with proper fuel management, reduces the power ramps that might cause fuel failures due to stress corrosion cracking.

Finally I would like to mention the incredible technical developments in CANDU maintenance. There is a full seminar on this topic next November here in Toronto. When I read the program I was impressed with the high-tech methods that are being used to study and maintain CANDU reactors. For example: for steam generators-- helium leak detection, acoustics, oxiprobe and eddy current inspections, and electrochemical noise techniques. Others papers include infrared thermography, predictions and measurements of pressure tube sagging, integrated software for corrosion control, retrofit of CAN6 seals into Pickering shutdown pumps, and even studies on the aging of the concrete in the reactors. It is great to see that such a rigourous maintenance program is in place; without it CANDU reactors would be in trouble.

In this half hour talk there are several topics that could not be covered; for example waste management, reactor safety, licensing, and operation--particularly the world's first use of computers to operate the stations. But I hope I have given you a brief glimpse into the complexity of the development of the CANDU reactor.

What has been the most significant aspect of the development program? I am certain that each of you would have your own choice; for me I would like to list three 1/ W. B. Lewis' insistence on neutron economy--this influenced almost every part of the design and operation. 2/ The tremendous cooperation within AECL, and amongst AECL, the utilities--especially Ontario Hydro, private industry, other government [federal and provincial] organizations, and several universities, [a prime example is the COG program] and 3/ The international cooperation that led to the input of so many ideas in the early part of the program to get it launched, and later to exchange scientific and technical data, to compare operational experience, and to incorporate new ideas as they arose. Without such cooperation the CANDU program would be different than it is today, if it existed at all. It is great to see that there is still international cooperation; I congratulate all of you for your ongoing efforts and your input to this conference. Best wishes for the future and HERE'S TO CANDU.