CANDU ORIGINS AND EVOLUTION - PART 1 OF 5

AN OVERVIEW OF THE EARLY CANDU PROGRAM PREPARED FROM INFORMATION PROVIDED BY JOHN S. FOSTER

Prepared by
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Summary:

While the name 'CANDU' was not adopted until the 1960's, the CANDU program can be considered to have started in early 1954. At that time, a team, called the Nuclear Power Group, was established to undertake studies intended to identify a potential Canadian nuclear power system. While the team operated under the auspices of AECL and was located in Building 456 at AECL's Chalk River Laboratory, its membership was drawn from a cross-section of Canadian utility and industrial organizations supported, as required, with "nuclear" expertise provided by AECL staff.

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The original team membership was as follows:

Harold Smith (Leader)	Ontario Hydro
John Foster	Montreal Engineering
Bill Cooper	Ontario Hydro
Dick Green	Babcock & Wilcox
Mel Berry	Ontario Hydro
George Haddeland	Shawinigan Engineering
Don Gregory	Brazilian Traction
Hank Merlin	Brazilian Traction
Bill Walker	BC Hydro

The makeup of the team reflected two primary considerations. Firstly, it was recognized that if a Canadian nuclear power program was to be successful, it would have to have strong support and acceptance by Canadian utilities and manufacturers and, secondly, AECL's in-house reactor engineering expertise was heavily occupied in completing the design of the NRU research reactor.

It is worth noting that, while the formation of the Nuclear Power Group represented a first major commitment to a Canadian nuclear power program, it evolved from earlier limited studies at Chalk River of possible means of producing useful energy from nuclear fission. For example, in 1952, limited consideration was given to generating electricity from an NRX in-reactor loop as a small-scale practical demonstration. In this same year, Bill Cooper and another engineer of Ontario Hydro were attached to Chalk River to learn something about nuclear reactors and associated technologies as part of preparatory exploration by Hydro of the possibility of utilizing nuclear fission as an energy source. They produced a report in which they favoured the concept of a homogeneous heavy water moderated reactor. W.B. Lewis scathingly criticized this report.

In 1953, Bill Bennett, then AECL's president, issued a mission statement which declared the development of nuclear energy for power purposes the prime objective of AECL. The Nuclear Power Group, whose mandate arose from this mission statement, had, by July of 1954, arrived at its first major, if only, at the time, provisional, design decision. This related to the reactor fuel. John Foster, on behalf of the Group, reported to the review committee, chaired by W.B. Lewis, that regularly reviewed the Group's ideas and progress that, although recognizing the greater potential efficiency of nested tubular or plate assemblies (the latter having been chosen for NRU), the Group had adopted the use of bundles of round rods in view of the uncertainties associated with the more efficient forms. Each rod would consist of a uranium metal fuel core clad in zirconium. This provisional decision was accepted by AECL's above-noted review committee, establishing an 'approval' mechanism which was thereafter followed as each decision point was reached. In these early stages of the program, a number of important 'givens' were assumed. These included the use of a vertical reactor core geometry contained within a steel pressure vessel, the adoption of heavy water cooling, on-power refuelling and control and shutdown of the reactor by mechanical control rods. In effect then, the concept represented a direct evolution of NRU with the pressure vessel allowing operation of the heavy water coolant at high pressure and, hence, temperature - essential if a usefully high thermodynamic efficiency was to be achieved for electricity production. AECL reports in the series designated 'NPG' describe the concept as it evolved during this 1954 and early 1955 period.

With the decision that Canadian General Electric (CGE) would play the lead role as the nuclear designer of the first small-scale prototype Canadian power reactor based on the concepts described above as developed by the Nuclear Power Group, the center of activity shifted to Peterborough from Chalk River in the summer of 1955.

The original contingent that began setting up shop at CGE Peterborough in April 1955 consisted of 13 engineers and scientists from Chalk River and an equal number from CGE. The new department created by CGE for the nuclear work was called the Civilian Atomic Power Department (CAPD). The term 'civilian' was chosen to distinguish it from American GE's Atomic Power Department then located at Schenectady, but soon to move to San Jose, California.

The organization of CAPD was as follows:

Ian F. McRae (CGE)	General Manager
Ian N. MacKay (AECL)	Manager of Engineering
John S. Foster (Montreal Engineering)	Head of Design
Wm. M. Brown (AECL)	Reactor Design
Ian Herd (CGE)	
Les. R. Haywood (PNL-AECL)	I&C Design
Gord Davis (CGE)	
Ralph Flemons (CGE)	
Warren Brown (CGE)	
Alex Hoyle (AECL)	Process Design
Lou Bissell (AECL)	Services Design
Dave Coates (CGE)	Fuel Design
Chick Whittier (AECL)	Chief Physicist
Fred Boyd (AECL)	Shielding
Dave Morgan (AECL)	Operations Advisor
Doug. G. Boxall (AECL)	Metallurgist
Wm. H. Bowes (AECL)	Stress Analyst
Mac Mcnelly (new hire)	Analyst
Ray Brown (new hire)	Electrical Design
Roy Tilbe (AECL)	Head of Development
Dick Johnson (CGE)	
Anse Taylor (CGE)	Chief Draftsman

Mel Thurling (CGE)	Manager, Customer Services
Tod Wilcox (CGE)	Purchasing
John Mathews (CGE)	Estimating
Jim Graham (CGE)	Construction
Ralph Candlish (new hire)	
Otto Laderach (CGE)	
Roy Olsen (CGE)	
Dick Duder (CGE)	Accounting

In addition, an important member of the team was:

Lorne G. McConnell	Ontario Hydro Superintendent, NPD

Early work on what was to be called the Nuclear Power Demonstration plant (NPD) centered on core design optimization studies. These studies, performed in the first instance at Chalk River by and under Arthur Ward assisted by Gene Critoph, suggested that the optimum cross-section area of a fuel channel should be about 50 sq. cm. For engineering purposes this translated to a circular fuel channel of 3.25 in. bore. The earlier noted decision to use rodded fuel assemblies was retained and a modified hexagonal array of 19 elements was chosen. The size of each individual rod element was chosen to provide a minimum inter-element spacing of .050 in. with the 19 elements fitted within the 3.25 in. channel diameter. The concept of utilizing a spiral wire wrap to ensure the inter-element spacing was adopted because it was judged that the spiral pattern would help to promote subchannel coolant mixing (later realized to be unnecessary). The minimum inter-element spacing of 0.050 in., recommended by Dave Coates at CAPD, accepted there, and informally approved at Chalk River, was based on heat transfer tests performed at Columbia University and other less applicable work at other American laboratories under US Govt. contract during and after the Manhattan Project.

Another key question which was addressed was the choice of materials for the reactor coolant system. It was known that the U.S. had selected austenitic stainless steel for the coolant piping and boiler tubing of their early PWR's. Doug Boxall, the CAPD metallurgist, recommended against this selection based on concerns regarding potential stress corrosion cracking in high temperature water. His recommendations were to use ordinary carbon steel for the pipework since the total surface area would be relatively small and to use Inconel for the boiler tubes. The CAPD team and the scientific community at Chalk River accepted these recommendations.

A further major decision was taken in October of 1955. This involved a change of the fuel core material from uranium metal to uranium dioxide and was based on successful irradiation tests of deliberately defected samples of such fuel performed for the U.S. navy in the NRX reactor at Chalk River. While the lowered uranium density provided by uranium dioxide relative to uranium metal resulted in a lowering of achievable burnup, uranium dioxide offered major advantages in terms of dimensional stability at high burnup and greatly enhanced corrosion resistance in the case of failures of the zirconium cladding. The decision to make this switch in fuel material was ultimately made by W.B. Lewis. Although Les Cook (Head of Chemistry and Metallurgy at Chalk River) and others had recommended UO2 for some time, Lewis had opposed it because of its adverse effect on neutron economy. The physicists at AECL and CAPD had been maintaining for some months predictions of NPD fuel burnup as new information on the reactor design and nuclear constants became available (Lewis called the graphic depiction of these predictions the 'fever chart'). As recalled by John Foster, the outstanding success of the above-noted defect irradiation tests on U.S. fuel coincided with an optimistic swing in the 'fever chart'. In any event, Lewis became convinced and journeyed to Peterborough to tell CAPD, 'out of the blue', to switch to UO2.

The question of cladding thickness had a significant influence on achievable burnup. Wolverine, a major U.S. tubing supplier, was consulted and based on their advice, a wall thickness of 0.020 in. was initially adopted by those responsible for the purchase of zirconium products at CAPD and by the AECL metallurgists, who duly reported it at a meeting of the technical review committee at Chalk River. W.B. Lewis challenged this as being unduly conservative and costly in terms of achievable burnup. His challenge to his metallurgists and the concerned CAPD engineers was: "Prove to me why it can't be 0.015 in." To meet this challenge, further experimental work was undertaken at Woverine which led to a reduction in wall thickness to 0.015 in. and then to 0.013 in. This development of thin, 'collapsible' fuel cladding represented one of the major steps forward in the Canadian nuclear power program.

While the foregoing design work was proceeding, centered at Peterborough, the Nuclear Power Group at Chalk River concentrated its work, during the period from early 1955 to late 1956, on design concepts utilizing recycled plutonium fuel cycles. During the latter part of this period, the Group looked at the possible use of pressure tubes rather than a pressure vessel. Work sponsored by the USAEC on the development of zirconium alloy pressure tubes for the Hanford N-reactor and the experimental PRTR appeared promising with tube manufacturing capabilities established in the U.S. at Harvey Aluminum and Chase Brass. In fact, the PRTR adopted a 3.25 in. pressure tube inside diameter and a 19-element fuel bundle geometry based, at least partially, on the above noted work in Canada. While the PRTR design proceeded with a vertical core orientation, the Hanford N-reactor adopted a horizontal orientation based on the earlier Hanford production reactors. This orientation allowed for a 'push-through' fuelling pattern employing short-length fuel bundles with no need for a mechanical connection between the individual bundles. Chalk River, led by W.B. Lewis, was attracted by this basic approach. At about the same time, the NPD project was encountering technical problems (late introduction of special containment provisions) and rising cost estimates. As a result, the CAPD design team was directed, starting in March of 1957, to investigate the possibility of converting the design of NPD from a vertical pressure vessel reactor to a horizontal pressure tube reactor.

By August of 1957, CAPD had produced a preliminary design that contained most of the essential features of the subsequent line of CANDU reactors, including, in particular, the stainless steel end fittings and their method of connection to the zirconium alloy pressure tubes, separate shielding plugs and seal plugs, the seal itself, the on-power fuelling machines, and the nature of those machines, and the choice of certain important materials such as for the primary reactor cooling system piping.

The new horizontal pressure tube concept retained the 3.25 in. channel and 19-element fuel geometries plus the 4-meter core length previously adopted for the pressure vessel design. A short-length fuel bundle was adopted following the Hanford N-reactor approach. The Nuclear Power Group had proposed a bundle length of 1 foot. John Foster recalls: "The 1 foot was clearly very arbitrary and seemed unnecessarily short. Consequently, I did a 'simple law of diminishing returns' calculation of the desirable subdivision of the length of fuel in a channel. I calculated the ratio of average to maximum burnup in fuel bundles, assuming a cosine neutron flux distribution along the channel, for subdivisions of the channel length into various fractions (at least 1/2, 1/3, 1/8 - maybe other fractions below 1/8). At 1/8 length the burnup would be very uniform. Shortly afterwards, a CAPD/AECL review meeting was held in the auditorium at Chalk River. At the end of my presentation on a more general subject, I mentioned that the 1-foot length suggested by the Nuclear Power Group seemed unnecessarily short, and that I had done a rough calculation that indicated 1/8th the channel length was short enough. Lewis jumped up and said that he had concluded, coincidentally, that the fuel bundle length should be 50 cm. (which is 1/8th of the NPD reactor length of 4 meters).[*] This was good enough for the Peterborough team, and the nominal 50 cm. length was adopted. A length of 50 cm. equals 19.685 inches. At that time in Canada, Imperial measure was still in general use. Engineers worked in feet, inches and simple fractions of inches except for 'finer' work where decimal fractions were employed. The designers of the NPD fuel channels and fuelling machines engaged on the preliminary design of NPD-2 in the summer of 1957, working to the 50 cm. nominal fuel bundle length, selected a design length of 19 1/2 inches. This became the standard length for fuel bundles for NPD and the subsequent line of CANDU reactors and reactors of this type designed in India.

"Related to the design of the fuel was the design of the fuelling machine. This was, I believe, the first on-power fuelling machine for a reactor using short, separate fuel pieces (slugs or bundles). At that time General Electric was the operating contractor for the USAEC's Hanford facilities. Because of the corporate relationship between CGE and GE, as well as the good inter-agency relationship between the USAEC and AECL, CAPD had a good working relationship with Hanford. The engineers there were not very sanguine about the on-power fuelling idea. The Hanford production reactors simply spat out channel-loads of fuel slugs during periodic shutdowns. On-power fuel changing had been explored on one or two occasions and abandoned. But in 5 months a few novice fuelling machine designers, headed by Dick Johnson, had produced a practical preliminary design that had all the essential features of the successful line of CANDU fuelling machines which followed - including, particularly, a rotating magazine with chambers for a full channel-load of fuel, as well as for plugs and other purposes, and combination rams to provide longitudinal and turning motions. The magazine made it possible to handle a full string of fuel without having a correspondingly long machine (space was at a premium because of the objective of having to fit the horizontal reactor into a rock excavation which had been sized for the earlier vertical pressure vessel NPD-1. The magazine required, of course, that each fuel bundle be separated from the string, and the string held in place while the magazine rotated. In NPD the fuel string was held, against the force of the water flow in the

[*] "There is a sequel to this story. In about 1960 the CEA of France embarked on the construction of a gas-cooled heavy water power reactor (EL-4) with horizontal tubes. It had about 8 fuel bundles per channel. A group of their physicists (including, possibly, a Monsieur Naudet) visited AECL's Nuclear Power Plant Division in Toronto sometime between 1960 and 1964. They asked how we had arrived at our bundle length. I told them the story. They said they had done something the same, and then had looked over their shoulder to see what we were doing. Since it was the same, they were content and went ahead with bundles of similar length. Some time later, they, like we, recognized that the basis was not correct but, like us, stuck with it. There is even a further sequel. Some years later I recounted this to Lewis and asked him how he had arrived at his selection of 50 cm. Unfortunately, he couldn't recall; but at another time he said that 50 cm. was the right length because is meant that the bundle could be handled manually and the size was very convenient for handling in manufacture and operation."

channel, by a latch in the outlet end fitting. A fuel carrier, operated by the rams, slipped under the end fuel bundle, and drew it through the latch into the magazine. Although machine length might have been a factor in the original design, the other merits of the magazine concept far outweigh this. The flexibility provided by the magazine has turned out to be one of the great features of the CANDU fuelling system."

CGE undertook the development of a manufacturing capability for the NPD fuel supported by the R & D facilities and personnel at Chalk River. While there was some argument as to whether or not CGE was to be 'given' the rights to this fuel technology under the NPD project agreement, AECL policy at the time, supported by Bill Bennett, Lorne Gray, and the AECL Executive Committee, was in favour of a 'turnover to industry' model. As a result, the practice of having Canadian industry undertake CANDU fuel manufacture on a commercial basis was established.

Building on the foregoing basic model, the Nuclear Power Group, in late 1957, evolved the concept of the bidirectional coolant flow and bi-directional refuelling pattern which was then adopted, marking the origin of another CANDU standard. John Foster recalls that W.B. Lewis told him of the bidirectional idea, which he attributed to Harold Smith, and that his mood was 'gleeful' as he talked about it.

Work proceeded rapidly in a number of design areas which required novel solutions and led to what became further CANDU standards. Bill Brown of the Peterborough design team proposed to John Foster a rolled-joint approach to the question of how to join the zirconium alloy pressure tubes to the stainless steel end fittings. John Foster's relevant experience consisted of his familiarity with rolled joints to connect boiler tubes to the steam and mud drums and sidewall headers in conventional boilers. These joints operated in similar, in fact more extreme stress, temperature, and water conditions, but, of course, without neutron irradiation and dissimilar metals. Brown's proposal seemed to Foster to be worth a try. Metallurgists at CAPD and Chalk River did not disagree. This approach was then successfully developed and adopted.

The flexible disc, pressure-assisted, end fitting closure seal was invented by Bill Bowes of the CAPD team and has been used in all CANDU-PHW reactors since.

Following the established NRX and NRU design approaches, aluminum alloys were chosen for the calandria vessel and calandria tubes. For the radial neutron reflector, consideration was first given to the use of graphite as was employed in NRX. However, with the horizontal core orientation the use of graphite appeared to present major engineering problems. As a result, a light water radial reflector was adopted following the NRU precedent.

Initially the design did not incorporate spacer devices between the pressure tubes and the calandria tubes. However, as is noted later in the discussion of Douglas Point, the garter spring concept evolved for Douglas Point was subsequently adopted for NPD in the form of a single Inconel wire garter spring located at mid-span. This offered a major advantage in the ability of the fuel channels to withstand the effects of creep sag of the pressure tubes.

Given the relatively small core size of the NPD reactor (~80 Mwt), it was practical to use a helium- gas-balance moderator dump system for reactor safety shutdown (a system proposed by

Ernie Siddall at Chalk River). The inherent simplicity of this approach was considered particularly attractive as compared to the use of mechanical shutoff rods, the latter having proved troublesome in the case of NRX. At the time, NRU was just coming into operation so its shutoff rods were not yet proven in extended use. A further perceived advantage of the gas balance moderator dump system was its inherent shutdown characteristic in the event of an accident which pressurized the moderator, e.g., the possible failure of a pressure tube and its surrounding calandria tube.

Turning now to the design of the primary heat transport system, the design adopted for the boiler was evolved by B&W. It consisted of a horizontal U-tube-and-shell heat exchanger coupled by risers and downcomers to a horizontal steam drum located above the heat exchanger. For the main coolant circulation pumps, the CGE design team originally had proposed the use of canned pumps developed in the U.S. by GE. Subsequently it was decided that vertical shaft-seal pumps would be employed. These offered the advantage of enabling the use of flywheels to provide an extended rundown characteristic in the event of power failure, thereby providing a better match between coolant flow and fuel heat output during the initial stages of reactor trip.

Turning now to the origins of the Douglas Point reactor design, in early 1958, AECL and Ontario Hydro decided to proceed with the conceptual design of a much larger reactor than NPD (now called NPD-2 to differentiate the design from the earlier pressure vessel concept). This led to the formation of the Nuclear Power Plant Division of AECL (NPPD) to be located in Hydro's A.W. Manby Service Center in Toronto. This marked a departure from the earlier 'turnover to industry' policy of AECL and was primarily the result of Harold Smith's views that Hydro would not want to be in the position of relying on a single commercial supplier of nuclear engineering services which would necessarily be in a monopolistic position. He felt that such services should be supplied either by Hydro 'in house' or, as a second choice, by AECL. Since Hydro was not in a position to undertake such work 'in house' and needed national input, the choice fell to AECL. Originally the plan called for a two-year conceptual study to be led by Harold Smith of Hydro, who had been appointed Manager of NPPD by AECL, with John Foster appointed as Deputy Manager. Smith was simultaneously appointed Chief Engineer of Ontario Hydro. He wished to study a vertical pressure tube arrangement, since he felt this alternative had been given inadequate consideration by the Nuclear Power Group, and some work was started in this direction. Two factors intervened however. Firstly, W.B. Lewis expressed a strong desire to see the horizontal configuration of NPD-2 retained. Secondly, the cancellation of the Avro Arrow program led the Federal Government to press for an acceleration of the large reactor program in the summer of 1958. As a result, the horizontal orientation was adopted since this could build directly on the experience being gained in the design and construction of NPD-2. The name CANDU was applied to this new reactor design. As the work got underway, John Foster succeeded Harold Smith as Manager of NPPD.

The NPPD team took a number of early decisions that departed from the NPD design. Firstly, on the suggestion of I.L. "Willy" Wilson, the NPPD chief designer, the calandria vessel material was changed from aluminum to austenitic stainless steel and the calandria tube material was changed from aluminum alloy to Zircaloy-2 since these changes provided a stronger vessel (it was, of course, to be much larger than the NPD vessel), with fewer material and water chemistry compatibility concerns. The use of stainless steel for the calandria vessel resulted in a change in the design of the radial neutron reflector. Since stainless steel is a relatively strong absorber of thermal neutrons as compared to aluminum, an external light water reflector could no longer be utilized. This led to the provision of an internal heavy water reflector by simply enlarging the diameter of the calandria vessel beyond that needed to accommodate the core proper. A major change involving the axial shielding of the reactor was introduced to improve maintenance accessibility to the fuel channel end fittings and feeder pipework. In the case of NPD, the axial shields were located outside of the fuelling machine operating areas at each end of the reactor. In Douglas Point the axial shields were moved inwards with the fuel channel end fittings penetrating the shields through lattice tubes. This allowed for direct access to the outer ends of the end fittings and feeder pipes during maintenance shutdowns of the reactor. The longer (nominal 500 cm.) core length of Douglas Point necessitated some means of maintaining the radial separation between the pressure tubes and their surrounding calandria tubes, particularly as the pressure tubes aged and were subject to creep sag. To solve this problem, Lib Pease, head of physics at NPPD, proposed the use of coiled wire springs which would surround the pressure tube in much the same manner as an 'arm-band garter'. This concept avoided the necessity of attaching anything rigidly to the calandria tube or the pressure tube, and, it was thought, provided scope for some rolling, rather than sliding alone to accommodate relative axial movement between the two tubes.

Turning now to the basic questions of fuel and refuelling for the larger reactor, John Foster recalls: "The 19 1/2 inch fuel bundle length for NPD had been arrived at unexpectedly quickly when Lewis endorsed the 8 bundles per channel (50 cm) concept, which I had mentioned rather extraneously and in a tentative way at a CAPD/AECL review meeting. I was very conscious that, whatever Lewis's reasons may have been, my 'law of diminishing returns' calculation was not a correct basis for choosing fuel bundle length. So when work began on the design of the horizontal 200 MWe reactor at NPPD, which would incidentally have a 5-meter long reactor, I arranged with "Willy" Wilson, the chief designer, to have Lib Pease do a proper calculation (with flux flattening and best reactivity data). The result was that bundles half the length of the channel would have quite uniform burnup, and division of the fuel into third channel lengths was the most that was necessary from a physics point of view. It was clear that we would rarely, if ever, want to exchange as short a length of fuel as 19 1/2 inches in a fuelling operation. It was decided to design the fuelling machine magazine to carry 39 inches of fuel per chamber. This materially reduced the number of chambers and the diameter of the magazine, and thereby facilitated the use of forgings rather than a casting for the fuelling machine body. As far as I can recall, the choice of 19 1/2 inch or 39-inch bundles was left open at that point. There were some very practical reasons for retaining 19 1/2 inch long bundles. They related to fuel development, manufacture, experimentation, and the value of future operating experience in NPD. In the event, the 19 1/2 inch bundle remained and has become standard for CANDU-type reactors. Of course the magazine made it possible to exchange a number of pairs of these bundles in a single fuelling operation, and it has become common practice to exchange 2,3, or 4 pairs at a time in CANDU reactors."

A further early decision arose from the wish of "Willy" Wilson to alter the refuelling arrangement so that the two fuelling machines, operating in concert, would have positive control of both ends of the fuel string during refuelling. This led to having fuel separators in the fuelling machines, rather than latches in the fuel channels, and fuelling with the coolant flow was adopted. These were fundamental differences from the NPD fuelling machine design; in fact, the two designs of fuelling machines were different in essentially all details. To understand this, it is important to remember that the two designs were only separated in time by about two years. As a result, the basic decisions regarding the Douglas Point fuelling machine design had to be taken before the NPD machines had reached even the testing stage. The fact that the two different design teams adopted quite different approaches is not surprising, given that both were working in a field of design where there was little background of practical experience.

Turning to another design feature of Douglas Point, it was decided that enriched booster rods would be utilized to provide a measure of xenon poison override. This followed NPD practice and was chosen to maximize neutron economy and, hence, burnup during normal operation (as compared with the use of adjuster rods which is discussed later in connection with the Pickering design).

A relatively novel design was chosen for the Douglas Point steam generators as compared to the NPD design - the latter having been patterned on the early Shippingport and N-reactor designs. For Douglas Point, the chosen design utilized a number of relatively small vertical ‘hairpin’ U-tube heat exchangers coupled to a common horizontal steam drum. Two such composite steam generators were utilized; one located at each end of the reactor as suited the basic ‘figure of eight’ heat transport system configuration. The attraction of the multiple, small heat exchangers lay in the idea that they could be replaced readily as units should problems such as tube leakage arise. Another change, relative to NPD, involved the choice of material for the steam generator tubing. NPPD metallurgist, Mike Bloor, proposed that Monel be used instead of Inconel on grounds of lower tubing cost and improved thermal conductivity. The latter was attractive because it would reduce heavy water holdup in the tubing (less total linear length of tubing required.) This proposal was accepted and proved a fortuitous choice, given the subsequent excellent performance of this tubing in Douglas Point and Pickering A.

A basic change was introduced in the primary coolant inventory control system for Douglas Point. In NPD, a pressurizer was used as the primary means of controlling heat transport system pressure. This approach had been well proven in the operation of the in-reactor loops at Chalk River. The Douglas Point designers were, however, particularly concerned with the high cost of heavy water which, at the time, had to be purchased from the USAEC. John Foster believes that this was a primary consideration which led them to evolve an alternative approach to heat transport system pressure control, viz., the use of a feed and bleed system which could then serve as both the means of adding and removing coolant from the heat transport system (as per the loops and NPD) as well as the means of maintaining the desired operating pressure in the system.

Moving on to Pickering, this design evolved from a study carried out by NPPD for a larger, 500 Mwe unit size which could be incorporated in a multi-unit station, following Ontario Hydro’s established multi-unit fossil-fuelled plant practice. The design was, naturally enough, an evolutionary development of the Douglas Point design as it had progressed by this point in time. The design also incorporated lessons learned from the early operation of NPD (started up in 1962).

An early decision involved the size of fuel channel to be employed. John Foster recalls: “The 500 Mwe capacity, two and a-half times that of Douglas Point, would mean major changes in the reactor. Its length would be 6 meters instead of 5. There would have to be about two and a half times as much fuel. With the extra length contributing about 22% of this increase, there would have to be about twice the cross-section of fuel. If 3.25-inch tubes were used, it would be necessary to have twice as many as in Douglas Point. This would pose several problems, such as the disposition of feeders, and the 20% greater core span. Incidentally, it would impede the development of even larger reactors. It was decided to use 4-inch (nominal) tubes. This invoked a strong negative reaction from the management at Chalk River - to our great surprise, because adoption of a 4-inch tube seemed mandatory. I do not recall knowing the reason for this reaction at the time, but I expect it was because of the new 3.25-inch power reactor component (mainly fuel) test loops in NRU. This is reinforced by the nature of the resolution of the disagreement. Chalk River was reconciled to the use of the larger tubes on the stipulation that the fuel bundles should employ elements of the same diameter as those for NPD and Douglas Point. The Pickering fuel bundle design, using 28 such elements and the standard minimum element spacing, resulted in a pressure tube diameter of 4.07 inches which became the standard nominal bore for all subsequent CANDU pressure tubes."

In addition to the change from 19 to 28 elements, another important change was introduced in the construction of the fuel. The early fuel for NPD and Douglas Point had short lengths of spiral Zircaloy wire wrap spot-welded to the fuel sheaths to maintain spacing between the elements, and to support the fuel within the pressure tube. For Pickering, brazed Zircaloy pads were used for these functions. Thin pads facing each other on adjacent elements maintained inter-element spacing without risk of wear of the fuel sheaths; and larger pads provided superior bearing support for the fuel in the pressure tubes. Joe Howieson, who was in charge of fuel design in the early days of NPPD, brought a preference for this type of construction from his development experience at Chalk River; but it took several more years of development before the process reached the stage that the brazed pads could be adopted for service. As a sidelight, the Indian DAE obtained the manufacturing technology for the wire-wrap design with the Rajasthan Atomic Power Project, and has retained it for all their CANDU-type power reactors. John Foster recalls that the DAE's reason was a health concern regarding the use of beryllium in the braze alloy for the alternative brazed pad design. In fact, subsequent history was to show that this was not a problem provided that appropriate protective means were employed.

The end shield design was altered, relative to Douglas Point, by having the inner end shield tubesheets serve also as the tubesheets of the calandria vessel, i.e., the two end shields and the calandria vessel became a single composite structure. This eased the alignment and support problems which had been encountered with the Douglas Point design since the calandria vessel was directly supported by the two end shields. Since the calandria tubes were rolled into the two common tubesheets, the end shield lattice tubes became, in effect, extensions of the calandria tubes. To eliminate the problem of acid formation encountered at Douglas Point in the air in the open annular spaces between the calandria and pressure tubes, these spaces were closed by bellows at both ends and the annuli were manifolded and connected to an inert gas system. The bellows allowed for differential axial expansion and creep between the tubes. As a parenthetic note, this design feature was later proven to be of great importance in limiting the rate of primary coolant loss when the channel G-16 pressure tube failed in Pickering 2. Had such a pressure tube failure occurred with the Douglas Point design, the consequences would have been much more severe.

A major change that was introduced in Pickering was the negative pressure containment system. Since Pickering was planned as a four-unit station, the use of a vacuum building connected to each of the four unit containments was judged to be cost-effective since the unit containment design pressure could be lower and a single dousing system contained within the vacuum building could serve all units. From a technical standpoint, the negative pressure containment system offered a major attraction in that any post-accident leakage through the containment structure, penetrations, etc. would be inward.

While moderator dump was retained in the Pickering design as the basic safety shutdown system, two problems became apparent as design and analysis proceeded. Firstly, the much larger core size severely limited the achievable rate of early negative reactivity insertion with mechanically practical dump port arrangements. Secondly, the large volume of moderator which had to be pumped back into the calandria following a dump would seriously limit the 'decision and action' time available for restart if the xenon poison transient was to be overcome. These considerations led to the addition of a number of gravity-operated shutoff rods to augment the moderator dump. The rods added substantial early negative reactivity following a trip. Furthermore, it became possible to avoid dumping of the moderator following the great majority of trips. This was accomplished through what was called the 'dump arrest' system. It operated by inhibiting dump valve actuation provided the measured rate of power decrease achieved by the shutoff rods alone was adequate to safely terminate the initiating transient.

The reactors for the 500 Mwe units were the first in the CANDU program to be so large that the peak neutron flux is not inherently constrained by reactor dimensions to remain reasonably centered in the reactor; as a result, the peak flux location can 'wander around'. An innovative regional control system, evolved by Ernie Siddall, was applied to these reactors to prevent such 'flux peak wandering'. The reactors were divided into 14 virtual zones in two axial planes, each plane containing one central and six surrounding zones. Each zone contains self-powered neutron detectors of the type invented by John Hilborn at Chalk River. Signals from these are used to control the quantity of light water (a neutron absorber in a heavy water reactor lattice) in a chamber located in the center of the zone. This system of regional neutron flux control, pioneered in the Pickering A reactors has become a standard feature of successive CANDU designs.

Turning now to the fuel handling system design, the fuelling machine and related fuel channel end fitting and internal hardware designs adopted for Pickering were based on the Douglas Point design with modifications to accommodate the larger fuel channel diameter and length.

As a digression at this point, it is worth noting the reasons surrounding the later decision, taken for the Bruce reactors, to utilize a fuelling machine and fuel channel end fitting design based on the NPD model rather than the Douglas Point/Pickering model. At the time when the basic design features of the Bruce reactors were being established (the late '60s), Canadian General Electric had already decided to vacate the field as a supplier of nuclear power plants. With the support of Ontario Hydro and AECL, it was decided that the CGE engineering team in Peterborough would concentrate on fuel handling and related systems. This, then, led naturally to the adoption of the NPD-type fuelling machine and fuel channel end fitting design since this is where the expertise of the Peterborough team lay. This decision also reflected the fact that the AECL fuel handling team was still heavily involved in completing the design and testing of the Pickering system and could not devote the necessary effort to the Bruce design. As a result, the two alternative basic approaches to fuel handling system design were kept alive. Subsequent history has shown that this was a fortunate decision since the continuing evolution of both designs has led to major ‘cross-fertilization’ of features to the benefit of both.