CANDU ORIGINS AND EVOLUTION – PART 3 OF 5

"Figure Of 8" Heat Transport System Arrangement

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Note added by D.A. Meneley[2] discussing the Darlington and CANDU 9 heat transport systems.

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Summary:

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INTRODUCTION

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NPD

As discussed in the monograph "An Overview of the Early CANDU Program, Prepared from Information Provided by John S. Foster" an early, and very basic, decision taken for the design of NPD-2 (this name was later shortened to NPD) involved the refuelling pattern adopted for the reactor. In order to avoid an axial end-to-end skewing of the flux and to maximize fuel burnup, it was decided that alternate fuel channels would be fuelled in alternate directions, thereby providing end-to-end core symmetry. Since the adopted mechanical refuelling arrangement called for the fuel bundles to be moved through the fuel channels in a direction opposite to the coolant flow, the coolant flow direction was therefore necessarily opposite in adjacent channels. As a result, coolant inlet and outlet headers were installed at each end of the reactor. This was a basic first step towards what, in later reactors, became the "figure of 8" arrangement. NPD did not employ a true "figure of 8" arrangement because the two outlet headers and the two inlet headers were paralleled, the former pair feeding a single steam generator and the later pair being fed from three 50% capacity circulating pumps.

DOUGLAS POINT

Douglas Point was the first CANDU reactor to employ a full "figure of 8" arrangement. The core arrangement was similar to that of NPD in that alternate channels were fuelled in opposite directions and the coolant flow alternated in direction between alternate channels. The arrangement differed, however, from NPD in that the refuelling direction and coolant flow direction were the same in each channel. Based on the author's recollection of discussions with the designers at the time, this scheme was adopted so that the highest power fuel bundles (those with relatively low burnup) would "see" lower temperature coolant, thereby increasing the margin to fuel element sheath "dryout". This was viewed as a more important consideration in the case of Douglas Point because fuel element ratings were higher than in the case of NPD. The mechanical refuelling arrangement adopted for Douglas Point differed from that of NPD and permitted refuelling in the same direction as the coolant flow.

The reactor arrangement adopted for Douglas Point differed from NPD in that the end shields were moved inward to positions immediately adjacent to the calandria tubesheets with the fuel channel end fittings extending through lattice tubes which axially traversed the end shields. The coolant feeder pipes were then located outside of the end shields. In the case of NPD, the feeder pipes were located in the spaces between the calandria and the end shields. As a result of this change plus the fact that the Douglas Point core length was greater, the distance between the feeder banks at each end of the reactor was much greater in the case of Douglas Point. Consequently, the use of an NPD arrangement, which coupled the two outlet headers and the two inlet headers, would have resulted in lengthy interconnecting pipework extending the overall length of the reactor which would have seriously increased the heavy water coolant inventory and, hence, cost. To overcome this disadvantage, it was decided to locate a steam generator (a steam drum and associated multiple heat exchangers) and its associated set of coolant pumps at each end of the reactor. This completed the full "figure of 8" arrangement.

A further feature of the Douglas Point Primary Heat Transport System (PHTS) arrangement is worthy of note even though not directly related to the "figure of 8" loop configuration. This involved the use of horizontal inlet and outlet headers located above the highest reactor fuel channel. NPD employed vertical headers, as did the original concept for a larger (200 Mwe) CANDU (AECL report NPG-10). It is the author's recollection, based on discussions with the designers at the time, that this arrangement was adopted to allow the primary coolant to be drained down (during maintenance outages) to a level within the headers just above the highest feeder connection while maintaining shutdown coolant flow to all fuel channels. This, then, allows direct maintenance access to the insides of the steam generators and primary coolant pumps. The recovery from the event at Point Lepreau in 1995, in which a large temporary plywood cover "bung" was mistakenly broken up and distributed through part of the heat transport system, was greatly facilitated by this header arrangement. Even though the Douglas Point designers had, no doubt, never envisaged such an event, the validity of their design judgment was well demonstrated!

PICKERING A & B

The basic Douglas Point "figure of 8" configuration was retained for Pickering A, and subsequently for Pickering B. However, instead of a single "figure of 8" loop, two parallel loops were provided, each serving half of the reactor core, the core being divided into two virtual 'zones' about a vertical plane of symmetry. The two loops were hydraulically separate from each other, thereby reducing the necessary capacity of the emergency core cooling system since a loss of coolant accident would affect only one of the two loops. In the case of the original Pickering A design, the emergency core cooling system (ECCS) utilized the moderator pumps to inject moderator heavy water into the ruptured primary loop (as was the case for Douglas Point). Injection capacity was, therefore, limited. The two-loop arrangement was retained for Pickering-B even though a separate high pressure light water injection system was used for ECCS instead of the moderator pumps. This change was later back-fitted to Pickering A to improve ECCS effectiveness.

BRUCE A & B

The initial design of the Bruce A reactors introduced two major changes in the heat transport system main cooling loop relative to Pickering. Firstly, while the steam generators and main cooling pumps were divided between the two ends of the reactor, as in the case of Douglas Point and Pickering, and the bidirectional flow arrangement through the fuel channels was also retained, the design embodied ring headers which effectively interconnected like headers at each end of the reactor. This change was introduced despite the economic penalty of added heavy water inventory in the ring headers, in order to permit relatively high power operation with one of the four main coolant pumps out of service. The design was later changed, effectively converting the ring headers back to conventional headers at each end of the reactor. This change was made in order to reduce the expected rate of coolant void increase in the reactor core following a major header failure which would otherwise lead to unacceptably high rates of positive reactivity insertion.

The second major change was the introduction of separate feedwater preheaters. In the case of Douglas Point and Pickering, the steam generators incorporated integral feedwater preheater zones at the primary coolant outlet end of the heat exchanger U-bends. With this integral arrangement, the primary coolant was uniformly subcooled prior to being pumped to the reactor inlet headers. The separate feedwater preheaters were introduced in the Bruce design to permit a greater degree of primary coolant subcooling for the high power central core region fuel channels; no subcooling was provided for the more lowly rated peripheral channels in the reactor core which were fed from separate inlet headers. While this arrangement added some complexity to the design, it offered the advantage of a better matching of coolant conditions to fuel channel power

CANDU 6

The CANDU 6 design (originally called CANDU 600) had its origins in conceptual design work carried out by the CGE team in Peterborough to adapt the multi-unit Pickering design to a single unit configuration which CGE hoped to sell to the international market and Canadian utilities (other than Ontario Hydro). When CGE decided, in the late 1960's, to abandon attempts to sell complete reactor projects, AECL "inherited" the concept.

At this early stage, the concept incorporated the basic Pickering "figure of 8" heat transport system loop configuration as described in Section 4. AECL continued CGE's earlier efforts to sell the reactor concept both domestically and abroad. In the early 1970's, these efforts were primarily centered on Argentina, which had indicated a strong potential interest in proceeding with a single-unit CANDU unit at the proposed Embalse site. As negotiations proceeded it became apparent that design changes would be necessary to reduce specific capital cost. At this time design, development, and equipment specification work on Bruce A had proceeded sufficiently that a number of possible cost-reduction steps could be taken with confidence for the single-unit CANDU. These included a change to 37 element fuel bundles from the Pickering 28 element design. This allowed the net power output to be increased to a nominal 600 Mwe while reducing the number of fuel channels from 390 to 380. The 12 steam generators and 16 main coolant pumps employed in Pickering were reduced to 4 larger steam generators and 4 larger coolant pumps, two of each being located in each of the two parallel heat transport loops. A relative reduction in steam generator heat transfer area was made possible by the decision to permit a low degree of boiling (nominally 4%) in the fuel channels. This decision was supported by the successful trial operation of NPD with boiling at the channel exit, and extensive loop irradiations at Chalk River with coolant boiling.

At a relatively late stage of detailed design of the new CANDU 600 reactors, analysis uncovered a potential difficulty with the basic "figure of 8" configuration in boiling operation. This had not shown up in the operation of NPD in boiling because, as noted in Section 2., NPD did not employ a full "figure of 8" configuration. The problem centered on the fact that with a "figure of 8" configuration, there were 2 zones of two-phase coolant (at the outlet end of each core pass) coupled by two zones of single-phase coolant. A mechanical analogue of this hydraulic configuration would be a flywheel incorporating two weights (the single phase zones), free to move rotationally, coupled by two springs (the compressible two phase zones) with relatively poor damping. Oscillatory movement of the weights superimposed on the basic rotation of the flywheel could occur at a resonant frequency determined by the masses of the weights and the spring constants of the springs.

As a personal note by the author, when this problem was first identified by the above-noted analysis, there was a concern that the problem might not be real but rather an artifact of the analytical code. In discussion of the situation with the analyst, the author recalled a personal experience during the out-reactor commissioning of the modified X-6 loop in NRX wherein an instability did arise when two decoupled two phase zones existed in the loop. One zone was within the electrically heated simulated loop test section and the other was within an electrically heated loop preheater upstream of the loop test section. This experience clearly indicated that the possibility of an instability existed and, hence, that the analytical prediction could not be ignored.

The approach adopted to solve this problem involved the addition of an interconnecting pipe to join the two outlet headers in each of the two main coolant loops. This interconnection hydraulically coupled the two voided regions, thereby removing the source of potential instability. Orifice plates were installed in two flanged connections within each interconnecting pipe. This arrangement was adopted to facilitate "fine tuning" of the orifice sizes to achieve optimal hydraulic damping based on subsequent commissioning test results. This "cure" proved effective and was adopted for all CANDU 6 and Darlington reactors, the latter having the same basic coolant loop configuration.

DARLINGTON

The Darlington heat transport system design drew most heavily on experience from design of CANDU 6. It employs a Figure of 8 configuration in two loops, with one pump and one steam generator at each end of the reactor, for each of the loops. The larger reactor size (480 channels vs 380 in CANDU 6) led to an arrangement with larger main components and longer end fittings. The reactor itself is nearly identical to that of Bruce B.

The specific geometry of the heat transport pumps, with a single volute and double discharge – both discharge pipes delivering water to the same reactor header – led to serious harmonic vibration of the system during startup and early operation. The forcing function of this vibration was found to be pressure pulses from the pump vanes, produced as the vanes passed the ‘cutwater’ openings to the volute. This vibration was greatly reduced, to acceptable levels, by changing the number of vanes on the impeller, and therefore changing the vane-passing frequency.

CANDU 9

This design was initiated early in the 1990’s to adapt the multi-unit Darlington design to a single unit configuration. With regard to the heat transport system, the most important design decision that was different from Darlington was the choice of a single Figure of 8 loop, instead of the two-loop adopted for the earlier design. Two inlet feeders are located at each end of the reactor. Inlet feeders of adjacent channels are connected alternately to each of these headers. This arrangement leads to an “interleaved” configuration with one-quarter of all channel inlets connected to one inlet header being distributed uniformly across the reactor. The principal reason for this choice of configuration was to eliminate the flux tilt that otherwise would follow the rupture of an inlet header during a loss of coolant accident. This configuration has the beneficial effect of reducing the magnitude of the power pulse resulting from this hypothetical accident.

A second major benefit of the “interleaved” heat transport system design is that further scale-up of reactor size, beyond the 480 channels as incorporated in the CANDU 9, would not lead to an increase the magnitude of power pulse resulting from rupture of an inlet header. The existing configuration can be easily scaled up to a 640-channel design.