Evolution of CANDU Steam Generators – a Historical View

by

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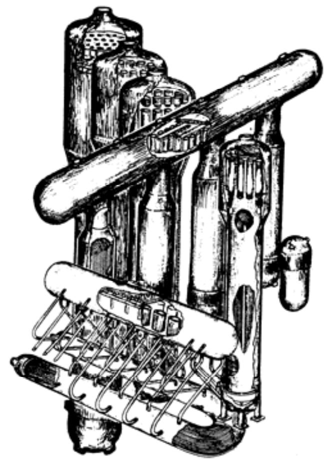

Abstract:

The evolutionary roots of CANDU Steam Generators are traced back to World War II era submarine designs. The now ubiquitous 'light bulb' design emerged as higher powers, the use of heavy water, and cost considerations favoured a design that was compact, vertical and exhibited superior heat transfer characteristics, high steam quality and robust operating capabilities. Fouling and adequate tube support proved a persistent challenge.

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1 Introduction / Preamble

One hundred years ago, Albert Einstein developed the scientific basis for the Nuclear Age. All associated disciplines took up the challenge and the Nuclear age was upon us. In Canada, Ernest Rutherford, a British Scholar at McGill University in Montreal, began teaching Canadians. In a short time a laboratory was set up in the city. Interest and development expanded so quickly that the Government of Canada soon began constructing a research laboratory at Chalk River with two research reactors capable of demonstrating the necessary nuclear processes required to design a full scale reactor.

During WWII, the USA asked Canada for help in the development of processes to produce enriched fuel for the bomb using nuclear reactors. When the war was over, the USA Army asked Canada: "What compensation was required?". The Canadian scientists stated that it would take at least 8 years for Canada to develop a nuclear boiler of their own and asked if the USA Army could do something to help Canada get a boiler design without delay. It was agreed that Admiral Rickover would give an order to Babcock-Wilcox (Barberton, Ohio) for a set of manufacturing drawings of a scaled down 20 MW version of the high power main turbine for a US Navy nuclear submarine. These drawings would be delivered to BW Canada Ltd (BWC) in Galt, Ontario under tight security control and the parts of the 20 MW boiler, also under tight control, would be produced and erected at Rolphton[3], just north of Chalk River. However fretting occurred in 6 years and became worse as time went on. Finally when the costs dictated, the unit was taken out of service.

It was in this way that the US submarine design became the starting point for CANDU steam generators.

2 Early Boilers

In the beginning of the industrial development of the western world, chemical processes used simple tubular heat exchangers to control the temperatures and create the reactions required to produce the end product. This involved transferring heat from one fluid to another. Thus heat exchangers were invented to do this. Many varieties were designed. Tubular designs, like Shell and Tube Heat Exchangers, are typically used in high pressure applications because tube geometry withstands pressure better than flat plate geometries, notwithstanding the smaller heat transfer area per unit fluid volume of tubes compared to plates.

The largest of these early types was the reboiler (see figure 1) which generated steam from water by extracting heat from the process fluid. These were very large capacity heat exchangers which did not produce high quality steam and were not very efficient. For electrical power generation, as the steam is used to drive a turbine connected to a generator, steam separation from the boiling

3 It is interesting to note that this boiler produced power to drive a synchronous motor to correct the power factor of the power line supplying electrical power to the town of Chalk River. It did so for 9 years.

water had to be improved in order to have long turbine blade life. The steam had to be dry enough not to erode the alloy turbine blades driving the generator. As fossil boilers had applications where dry steam was required, steam drum internals had been designed with cyclone steam / water separators for the turbine application. Therefore the next logical step to the nuclear application based upon known technology was to combine a reboiler type heat exchanger with a fossil steam drum.

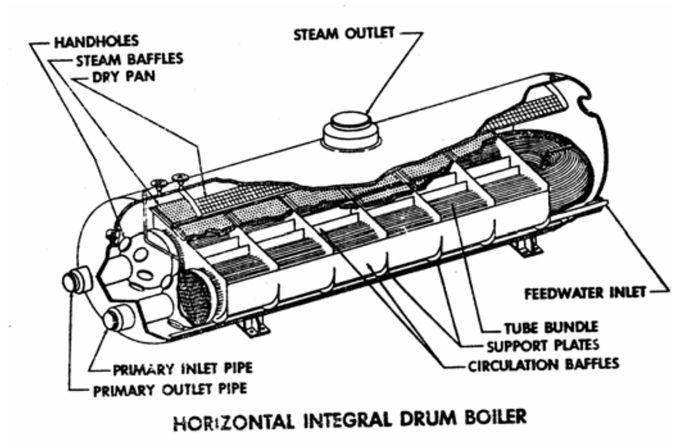

Figure 1

These were the first types of submarine boilers in service as shown in figure 2

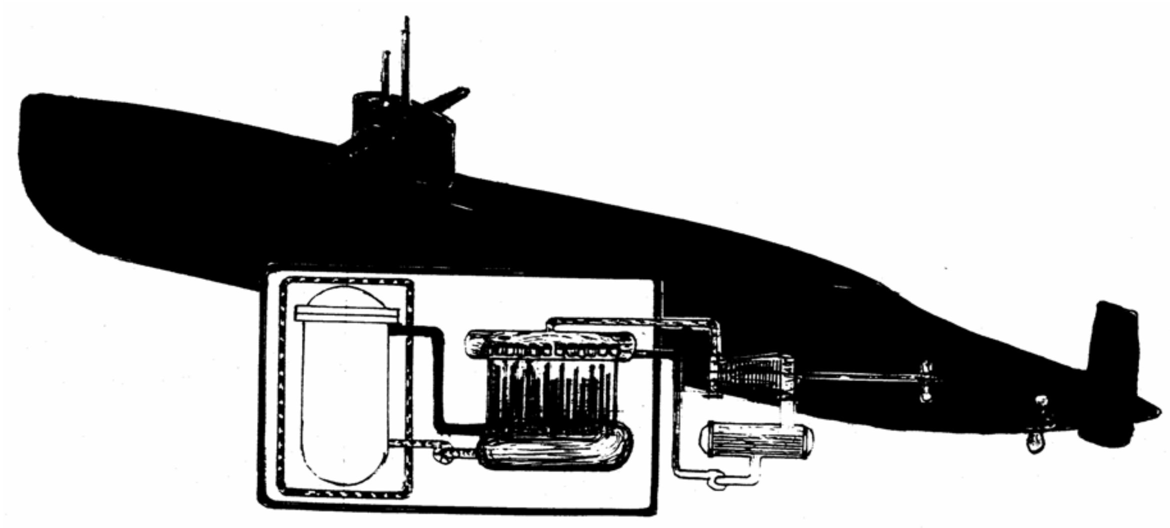

Figure 2 Submarine boiler - horizontal steam drum with cyclone steam separators.

All these arrangements with horizontal steam drums above the heat exchanger limited the maneuverability of the submarine. As the submarine either rose to the surface or dove to submerge, since the steam drum‘s centre line was parallel to the submarine’s axis, the water level in the drum sloshed to the bow or the stern of the drum and flooded the cyclones at either end sending alternating slugs of steam and water to the turbine with erratic pulsating loss of power. Thus the need arose to design a vertical drum with suitable separators, such that these would function as required even with violent fluctuations of water levels in the drum, as shown in figure 3.

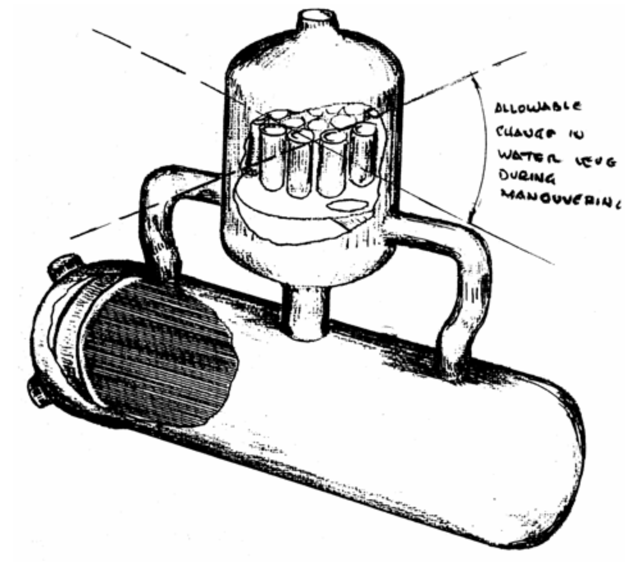

Figure 3 Vertical drum.

At the same time, a vertical steam drum, in the commercial application, changed from a long horizontal drum to a vertical drum to reduce the diameter of the containment vessel and increase the number of steam generators which could be accommodated in it, thereby increasing the total MW rating of the plant. Thus the development of vertical steam drums, in submarines and in commercial plants, went hand in hand. In fact, Babcock Wilcox Canada (BWC) commercial nuclear power and BW Lynchburg labs (US Navy submarines) worked together, equally sharing the costs to develop steam separators for both applications.

So in the beginning of the peaceful use of nuclear power generation both USA and Canada used boilers based upon US Navy boilers designs which had been secretly developed for submarine propulsion by US companies, such as BW (USA), and no doubt Combustion Engineering (CE) and Foster Wheeler (FW) for the US Navy.

Since these designers had knowledge of fossil steam drum design, it was natural that they chose an existing piece of equipment for steam separation. Thus the first US Navy Submarine boilers consisted of a reboiler set of U tubes inside a drum. This heat exchanger was connected, via risers and downcomers tubes, to a fossil steam drum over the top of the reboiler exchanger. These efforts were a closely guarded secret and classified documents were difficult, if not impossible, to obtain. The exception was the Nuclear Demonstration Plant (NPD) at Chalk River, a 20 MW Boiler pro-rated from a 50 MW US (Navy Submarine) boiler plant and a Demonstration Plant at Shipping Port (USA) based on PWR technology.

3 NPD, Nuclear Power Demonstration Plant

At the same time as the US started their development of Nuclear Power for commercial purposes, Canada started work on Canada's peaceful use of the Atom, which was to be a clone of the US PWR cycle. However Harold Smith of Ontario Hydro (OH) and W.B. Lewis of AECL convinced the establishment that it would be a waste of research dollars for Canada to develop a variation of the enriched fuel cycle, when the Heavy Water natural fuel cycle, which had a great many good variations going for it, would be overlooked. Its greatest advantage is that it did not use enriched fuel, a by-product of the enrichment process to make bomb material with all the detrimental environmental by-products associated with plutonium production. Thus the Canadian Deuterium Uranium cycle (CANDU) was borne.

At this time the Chalk River Labs were working together as a joint effort of US, UK and Canadian scientists assigned to the Manhattan (Bomb) project. So there was a "restricted" free flow of nuclear information between the three countries. Canada, to even be close to the target date to demonstrate this new application, had to have a boiler design immediately. It doesn't take much imagination to believe that the US scientists at Chalk River made arrangements with US navy to send prototype drawings of a 20 MW boiler - unclassified - to help Canada get started. Figure 4 illustrates the boiler design for NPD. BWC who fabricated the unit shipped it to DesJoachins (Chalk River), Ontario, the site of Canada's Nuclear Demonstration Plant (NPD). It might be of interest to note that the USA was proceeding to build a Demonstration Plant, at Shipping Port in the USA, of 50 MW capacity at the same time. The Canadians were the first to go on-line, producing power several months earlier than the Shipping Port Station.

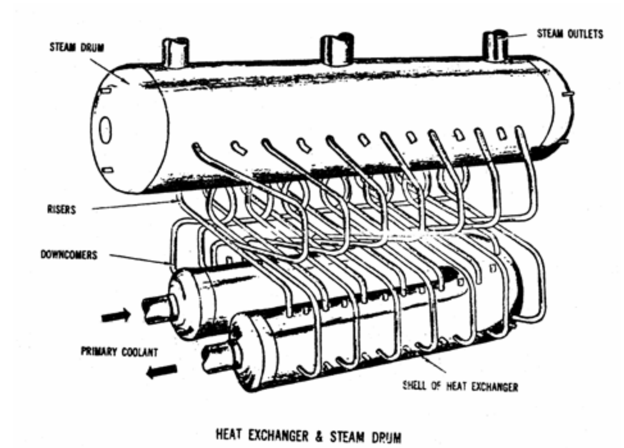

Figure 5 NPD 20 MW boiler.

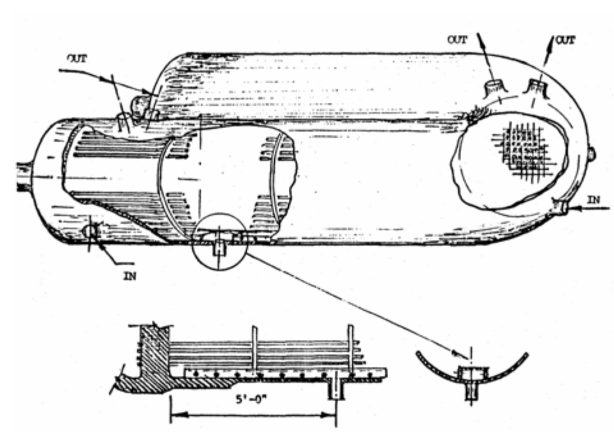

Figure 4 NPD boiler tube fretting sketch.

The NPD boiler sprung a boiler leak after it went in service. The prime author of this paper, John Dyke, then BWC project manager for NPD, was one of the investigating team and noted that fretting occurred in the area associated with blowdown flow, alerting him early in his career of the possibilities of flow and boiling induced failures and of the importance of proper tube supports. He later

reported:
"The evidence shows that the method of tube support design is critical if tube failures are to be avoided. The mechanism of failure of inconel is not yet fully established but local boiling to dryness initiates the attack. It can be shown that drilled support plates with parallel sides and small clearances around the tube can promote adverse conditions. The lattice bar type tube supports with line contact on the tubes and large open areas have proven to be successful and no failures are reported either from dryout or vibration." [DYKE 1970]

4 Douglas Point

With the success of NPD, AECL now started to plan the CANDU program in earnest. They offered nuclear related courses to Canadian industrialists. Then AECL set up a boiler competition and invited Canadian boiler manufacturers to develop a boiler suitable for the CANDU conditions (which were different from the US PWR cycle). This course of action was necessary because none of AECL's engineers or BWC engineers nor any other set of engineers in Canada were technically involved in the design of the NPD boiler. The BWC engineers were only involved in the production of the drawings from other sources of information, such as the US Navy, the shop fabrication of the pressure parts, and erection at the site. Canadian engineers had to guarantee the properties of the heavy water and set the heating surface.

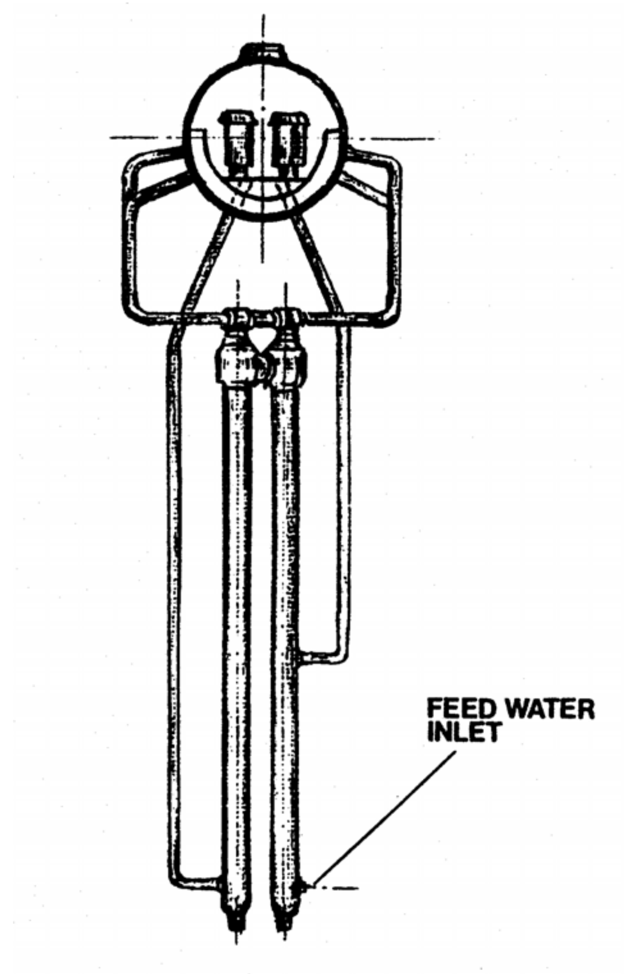

Figure 6 CE design for Douglas Point Boilers.

The successful completion of NPD led to a series of strange unconnected commercial events, none of which contributed to AECL's objective to build up a Canadian group of competitive boiler companies to supply boilers for CANDU.

Combustion Engineering (CE) won the boiler competition for the most suitable design (figure 6) and was no doubt influenced by CE's connection to the US Navy work being conducted within their corporation. Thus they used a horizontal fossil-type steam vessel, similar to NPD which was an AECL choice. To meet the CANDU conditions for the steam conditions and cycle parameters they used vertical hairpin heat exchangers with one vertical leg for boiling heat transfer and another vertical leg for the preheater, both joining at the top to form a steam water mixture which entered the steam drum, in which the steam and water were separated. The dry steam was piped off to the turbine and the water returned to the boiler leg.

AECL took this design and modified it for the Douglas Point Station (figure 7) adding some of their own ideas and unfortunately, as it was later determined, used Westinghouse's tube support system of drilled hole plates for tube supports. Also there were no tube supports specified for the U bent tubes in the cross-over sections between the boiling and the preheater legs of the hairpin heat exchangers. Fretting occurred in this area. Thus the first two CANDU boilers were influenced by submarine technology and AECL input.

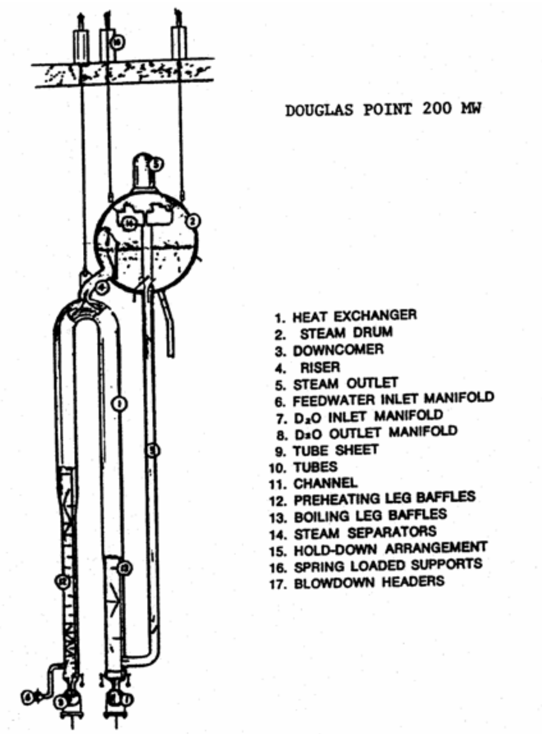

Figure 7 AECL design for Douglas Point.

Boilers for the Douglas Point station were awarded to Montreal Locomotive Works (MLW) based on the lowest price. This order was probably the largest heat exchanger order and the most complicated design MLW had ever handled. With the design faults as noted above, MLW did not have the depth of engineering talent to challenge AECL's designs. There could have been a desire on AECL's part to be in a position to be seen as providing the design aspects, and thus to be in full control of the boiler design process and hence the development of the first full scale commercial CANDU boilers. So AECL approved MLW to build these boilers.

5 Pickering A

Pickering A specification followed which was an up-rated 500 MW version of the 200 MW Douglas Point boilers with no changes. The acceleration of Ontario Hydro (OH) building nuclear plants and abandoning fossil fired plants entirely meant the loss of the major portion of BWC's market. BWC had not submitted a prototype design at the conclusion of the boiler competition nor did they bid on the Douglas Point station. But now they had to do something positive! BWC's management, in discussions with the USA parent, concluded that BWC had to seriously tackle the nuclear option and go after the competition to become a major player. Up to then, they had taken "a wait and see" attitude.

BWC thus set up a new nuclear proposal department (Dyke to start with) to conduct research into world wide experience published in the technical press, AECL published data on world wide failures, etc. The US parent stated they would support BWC as much as possible, but noted that they did have restrictions put on them by the USA Navy. However, BWC would have access to information based on the commercial PWR, the "Once Through Steam Generator" (OTSG) and it's Nuclear Steam Supply System (NSSS} and water technology. BWC's proposal dept (of one) started to prepare a bid to specifications for the Pickering A station and to design out some of the weak features carried over from the original Douglas Point design.

In parallel to the US parent support to BWC as noted above, the proposal department at BWC wanted to offer a steam generator based on the PWR criteria. The BWC proposal engineer knew, from work done by one who had participated in the boiler competition, that a PWR steam generator applied to the CANDU cycle would not compare favourably because of the high cost of heavy water. A CANDU application required a lower heat transfer surface area to minimize the primary fluid volume and, thus, the cost of heavy water. There was incentive to design a different newer boiler than that used in the PWR (figure 8). Increasing the tube-side fluid velocity gave a higher heat transfer coefficient. Given a fixed primary side mass flow, velocity could only be increased by lowering the flow area, ie a lower number of tubes. Having longer tubes brought the total heat transfer area back up to the required level but now introduced the need for more tube supports, and with it came more fretting and vibration issues of unknown origin.

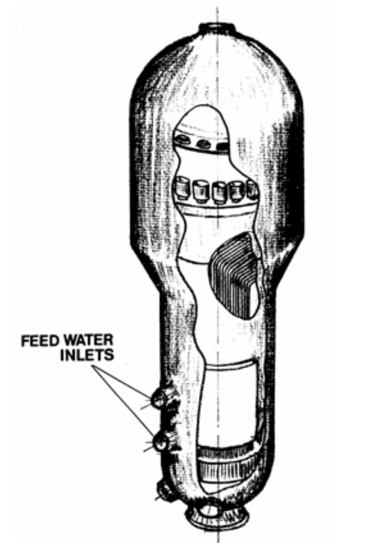

Figure 8 Combustion Engineering design of a RSG for the NA market.

Canadian management were appraised of this and was asked to reverse its decision and allow the proposal department to design a Vertical Recirculating Steam Generator (RSG Boiler) with an internal economizer which would evaluate more favourably in the CANDU cycle. This would be a first of a kind for the Canadian industry. They agreed and the proposal dept went ahead with an RSG vertical U tube Boiler with an internal economizer and a vertical steam drum as shown in figure 9 (another first for CANDU). Note that this followed along with changing to a vertical steam drum for the submarine to avoid excessive water level swings when maneuvering. This change also permitted the inclusion of the internal economizer as a part of the boiler bundle. The result was a very economical arrangement.

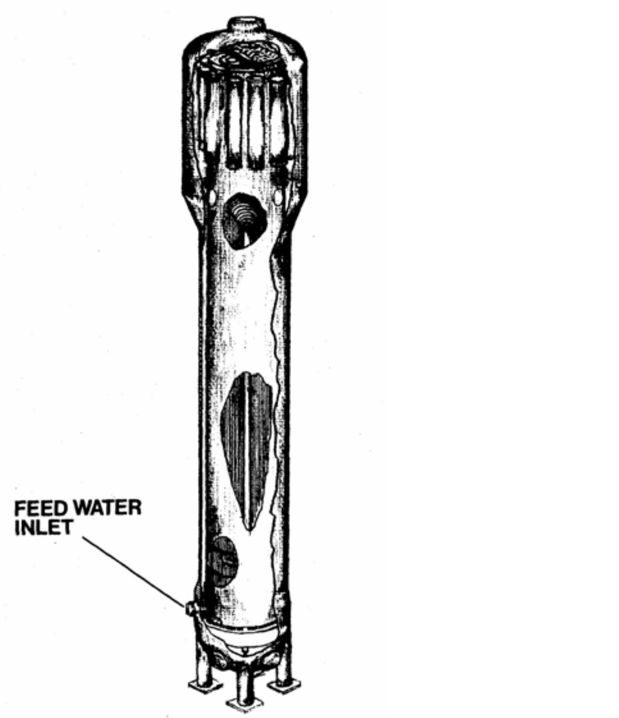

Figure 9 The first boiler in North America with design features that showed that a nuclear recirculating steam generator (RSG) could be designed to survive its hostile environment.

The commercial pricing decision for the alternate bid was easy. Industry knew the sale price of Douglas Point when it was built. Industry knew that MLW had problems and cost overruns, and if they wanted to stay in business they had to quote a reasonable repeat price. MLW was not capable of designing a new boiler. BWC had to bid to specs and therefore knew MLW's probable costs for the base bid for a 500 MW size. BWC knew what their costs were for both the base bid with hairpin heat exchangers and, the alternative design of a boiler with an internal economizer. Thus they were able to set the sale price of the Pickering A alternate design at a value that AECL could not refuse. This tactic got BWC into the nuclear power plant business with OH. As a result, BWC received all the CANDU orders in Canada, some at cost plus because of schedule constraints but lost one overseas contract to Foster Wheeler (FW).

The downside of this result was threefold:

1. There was no direct competition for BWC in Canada.
2. AECL engineers became judges of their own problems with no hard boiler experience to back them up. Long delays in getting solutions resulted (e.g. the Bruce B decision to use horizontal or vertical drums).
3. More seriously, as all first generation boilers in the world came on line about the same time, they all suffered from fretting problems as a result of various design detail faults.

AECL Laboratories and many others set about conducting experimental work on tube fretting. The results which they published were either incorrect or misinterpreted by design engineers. The proper method of tube support was suppressed because Westinghouse, the most prolific of all steam generators makers in North America insisted on building boilers with drilled hole tube support plates (see figure 10 for a comparison of the competing designs). AECL subscribed to the Westinghouse design, supported by the experimental work done at Chalk River Laboratory's experiments, and believed it was the only way to build a proper tube support system. As we now know, all Westinghouse units failed and had to be replaced. Westinghouse is no longer in the nuclear boiler business and their legacy is that the whole industry suffered from their strong influence. The use of drilled holes cost Canada dearly as this decision led to the result that such Canadian nuclear boilers had to be retubed.

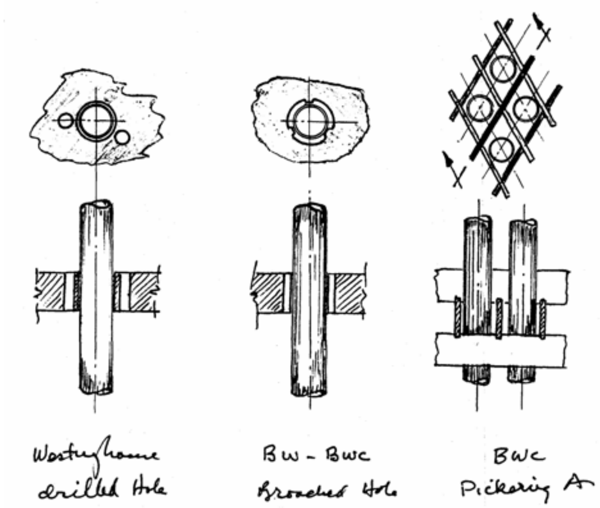

Figure 10 Illustration of drilled hole, broached hole and lattice bar designs.

Initially Pickering A used a lattice bars system of tube supports. This was not designed properly and was too weak to support the weight of the tube bundle. The bars bent during shop handling and field erection. This lead to the belief that lattice bars should not be used for new stations even though the Pickering A lattice bar system was redesigned and provided excellent in-service results, the best in North America. Consequently, subsequent designs used broached holes.

6 Bruce A

Because of the early Pickering A experience with lattice bars and the common use of rigid tube supports worldwide, AECL and/or OH did not accept an improved version of lattice bars despite Pickering A's excellent in-service performance. AECL and industry were warned in 1970 that drilled hole plates were a poor choice and would fail. Hence, all boilers (post Pickering A) up to and including Darlington were ordered with broached hole plates (see figure 10), a tube support system used in BW USA commercial nuclear boilers. In time, these devices also failed but not to the same degree and not as quickly.

Because BWC bid lattice bars for the contract for Bruce A and because AECL/OH would not accept these, much-time was consumed in negotiations to settle the design details. To comply with customer demands, BWC switched to broached hole plates. It will be noted here that accepting broached hole plates meant that the U bend supports had to be redesigned from scratch. This resulted in a U bend support system called scalloped bars. Because of the results of the experimental work done at Chalk River, scalloped bars were designed to hold the tube in the U bends with small hole clearances. The whole structure was very stiff so that, supposedly, the tubes would not fret because the tubes were clamped together by the scalloped bars. As a result the arrangement held the tubes in the bundle tightly thus preventing the tubes from expanding independently when subjected to differential thermal stresses. This produced a compressive load on the tubes in the bundle.

The tubes in the bundle, being held straight by the broached plates and under these huge compressive loads, buckled and bent out of line such that the outside surface of the tubes were scratched and marked by the lobes of the broached hole plates. The damage was so extensive that it was decided that all boilers under construction in the shop and being erected in the field had to be retubed. If lattice type U bend flat bars supports had been used, this damage would not have occurred since, with this design, the tubes would have been free to expand.

The repair costs and the costs of the resulting delays in the construction schedules were estimated to be in excess of $75,000,000. This was more than the net worth of BWC. Managements of BWC, OH, AECL and BW USA spent many hours to determine what actions to take and how to split up the costs. It was decided to proceed with the retubing of all boilers that were not in operation. It is curious to note that the design review team for the rebuild program did not include any of the original engineering personal of the Pickering A design team, thus precluding any chance to rethink the lattice tube support system. As a result, the rebuilds were designed by those who believed in and favoured the broached hole plate system of supporting the tubes. As these rebuilt boilers came on-line and were inspected it was evident that the boilers were in deep trouble and had to be rebuilt.

These defects did not show all at once but the evidence appeared over a period of time as boilers were inspected at shut downs and maintenance took place. It became clear to a few engineers that the tube support system played a large part in the life expectancy of the boilers as noted above and in the literature in 1970.

Quite apart from tube support issues, AECL specified a horizontal steam drum for this third generation CANDU (Bruce A) when all other boiler manufacturers throughout the world, not just the USA and Russia, had dropped this arrangement for a vertical integral vessel attached to the top of the U bent tube heat exchanger shell (dubbed the light bulb design). The light bulb design makes for a compact arrangement and permits a smaller diameter containment vessel. However, the Bruce A steam generators lie primarily outside the containment walls so this advantage is moot for this plant. Further, Pickering A exhibited boiler level control issues that would be alleviated by a horizontal common steam drum design (figure 11). A preheater that was separate from the boiler was chosen so that the inner zone of the reactor could be maintained at a lower temperature and, thus, eliminate boiling in the primary heat transport system.

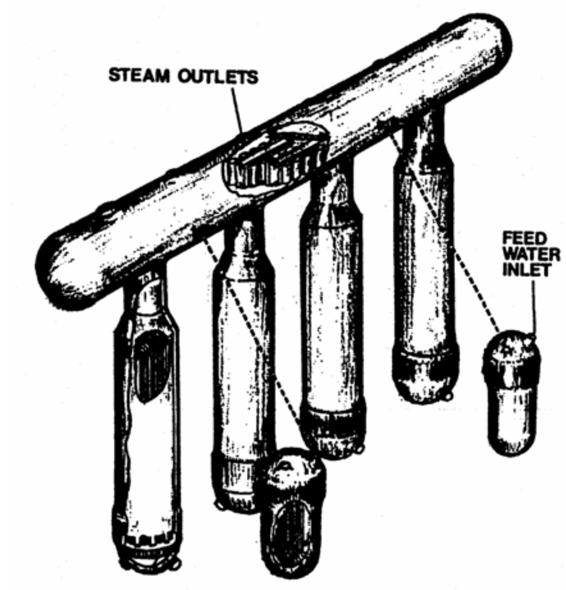

Figure 11 Bruce A common steam drum and separate preheaters.

During negotiations for Bruce A, AECL asked Dominion Bridge for a price on the steam drums, BWC for a price on the preheaters, and Westinghouse for a price on the boilers only. Westinghouse had a PWR boiler arrangement to offer; a ‘one off’ new boiler design would be too expensive. With a great deal of maneuvering, saner minds prevailed and BWC eventually received the order for all items.

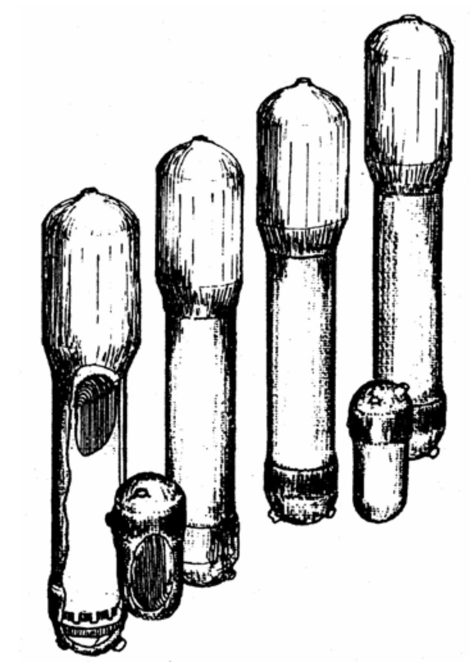
Figure 12 Bruce B

7 Bruce B

All this work caused the total program to slip behind and the time for ordering Bruce B was in jeopardy. The question arose whether to duplicate the cross drum or change the design to integral steam drums. The debate over whether to change or not came about because a stress problem arose from the Bruce A drum design. The very long drum, coupled with variation of water level during abnormal operating conditions, could give excessive top to bottom temperature gradients, causing the drum to bend either concave or convex, raising concerns about high stresses. Because of this, the plant was restricted to reduced power until the stress points were examined in detail. The loss of revenue from the reduced power was significant.

So to avoid future delays after the AECL board had made a decision, AECL completed drawings for both designs so when a decision was reached the engineering was complete for both alternatives, work could start immediately and the schedule would not be delayed unduly. The request for a license was sent to the AECB and during their deliberations there was an impasse. An inspector called BWC and asked BWC for a tie breaking vote with reasons. The next day AECL was given the go ahead to build integral drums and the cross-drum boiler became obsolete, presumably forever.

8 Darlington

Concurrently with all the above activities for Bruce B, the specifications for Darlington were issued and bidding proceeded. Once again discussions arose on the method of tube support system to use. The order was based on BWC providing broached hole plates and scalloped bar U bend support systems, despite evidence to the contrary.

Three engineers, one each in BWC (Dyke), OH (Jackman), and AECL (Akeroyd) took it upon themselves to push hard to change Darlington to lattice bars and flat bar U bend supports. This occurred as there were changes made in engineering management at BWC and AECL. The support for this change came from the results of wind tunnel tests at McMaster University [WEAVER 1982], which proved that a flat bar between the tubes in the U bends of the tube bundle would stop them from vibrating. This was contrary to the findings of most other laboratories. Furthermore, the wind tunnel tests suggested that flat bars, i.e. lattices bars, would be more effective in the tube bundle than broached hole plates. Unfortunately, funding was not provided for much further work at that time, even though the test results suggested otherwise. Weaver and Schneider [WEAVER 1982] also concluded that clearances should be kept small to prevent momentum buildup and resulting impact damage when tube motion instabilities are induced. This may indeed be a valid conclusion for air flow over tubes but may not be true for two phase water flow where the cushioning effect of bubbly flow favours larger clearances.

At any rate, the evidence of this bench test was sufficient for the three above mentioned engineers to convince their managements that broach hole plates should be abandoned and replaced by lattice bars. With this change Darlington boilers jumped into the lead in world boiler performance. Up until then, Pickering A, with its lattice bars support system, lead the world in in-service performance (the least number of tubes removed from service). BWC entered the USA rebuild market, replacing over 40 units which had failed. This gave BWC about 10 years of work replacing boilers for the USA utilities.

9 Concluding Remarks

From war-time and post-war circumstance, the current CANDU steam generators evolved from submarine-based heat exchanger designs to highly efficient, high performing, compact, robust and cost effective light bulb designs with integral preheaters and lattice bar supports for both CANDU and PWR type nuclear power systems. This design was pioneered by Babcock and Wilcox Canada.

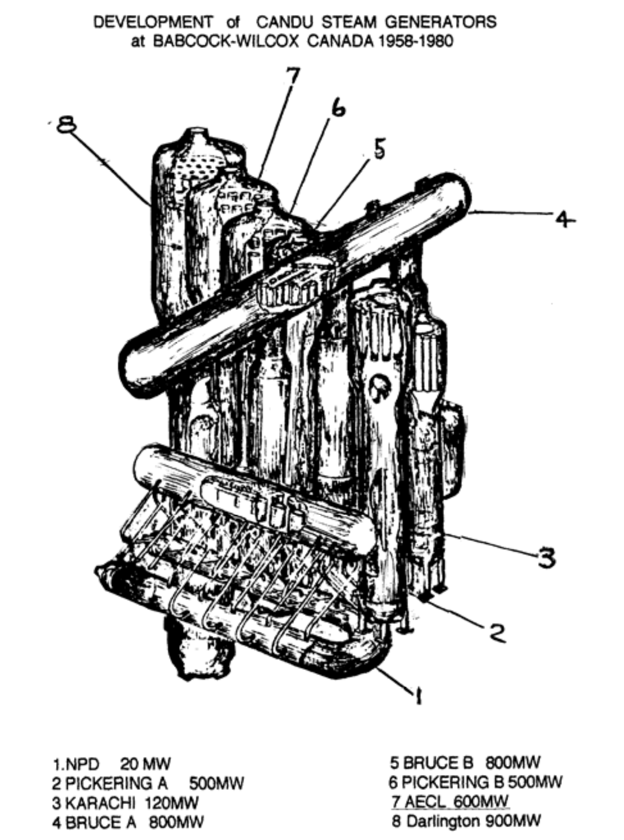

Figure 13 A collage of BWC designs.

10 About the Authors

John M. Dyke B.A.Sc., P.Eng

John was involved in steam generator design for 35 years, from 1945 to 1980. He lead the design team for the Pickering A nuclear station in the mid 1960s. They were the first with internal economizer and integral steam drums. The 48 steam generators at this four-reactor station have had exemplary performance. John obtained his B.A.Sc. in Mechanical Engineering from the University of Toronto in 1943 and joined the Royal Canadian Navy Volunteer Reserve as an Engineering Officer posted with the Royal Navy doing convoy duty in the Atlantic and the Mediterranean. When he returned to Canada he worked at the Naval Research Establishment in Halifax developing anti-acoustic torpedo gear. Coincidentally, these were parallel rods that vibrated in water streams. After the war John did steam boiler engineering at several firms and became Chief Engineer of Dominion Bridge's new boiler department in 1958. Here he attended a special course on nuclear design and submitted bids for early nuclear steam generators and reheaters. In 1964 he joined Babcock and Wilcox Canada, first as a project engineer on fossil-fired boilers and then to head up the new nuclear steam generating section where they developed a new 500 MWe design for Pickering A. He is a registered professional engineer with the province of Ontario. He has been honored by the American Society of Mechanical Engineering as a life member for outstanding lifetime achievement. The Canadian Nuclear Association also honored him with their Outstanding Contribution Award for designing the steam generators used in CANDU stations. John retired from BWC in 1980.

Wm. J. Garland, B. Eng., M. Eng., Ph.D., P.Eng.

Bill specializes in reactor physics and thermalhydraulics system design and simulation. From 1975 to 1983, he worked in the Canadian Nuclear Industry specializing in CANDU heat transport system analysis and design. The major effort from early 1980 to mid 1983 was in heat transport system stability investigations. This included pre- and post-test analysis, coordination of AECL's process team, test planning, and liaison. Presently, he is Professor of Nuclear Engineering in the Department of Engineering Physics at McMaster University conducting analysis and research of the MNR nuclear reactor systems. While on research leave at Harwell Nuclear Labs in England, Bill conducted knowledge engineering for heat exchanger selection and developed a heat exchanger selection computer code which became a commercial product distributed through the international company HTFS. In addition, computerized water property functions developed at McMaster are in use in about 13 countries by over 120 users in 51 institutions and major engineering firms worldwide. He served as Department Chair from 1988 to 1994 and was Director of MNR for 1994 to 1995 leading up to the decision to revitalize reactor operations. He is serving as Secretary / Treasurer and Program Director for UNENE.

He is Academic Director for CANTEACH. In this role, he had the honour and good fortune to assist John Dyke in capturing the seminal aspects of the evolution of CANDU steam generator designs. There are few activities as fulfilling as knowledge engineering of domain experts. For this, a sincere and warm thank you to John.

11 Acknowledgements

The authors wish to gratefully acknowledge CANTEACH sponsorship from the COG organization.

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