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"Evolution of CANDU Steam Generator Design (1958-1980) – A Personal View from J.M. Dyke"

by J.M. Dyke
(previously published as CSME History Cttee Working Paper 10/1997 – Apr 1997)

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PO Box 40140, Ottawa ON K1V 0W8
+1 (613) 400-1786 / admin.officer@eic-ici.ca / http://www.eic-ici.ca

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CSME History Committee

WORKING PAPER 10/1997

EVOLUTION OF CANDU STEAM GENERATOR DESIGN (1958-1980): A PERSONAL VIEW FROM J.M. DYKE

by

J.M. Dyke, P.Eng. (Retired)
Co-author: S. Roy, P.Eng. (Monenco AGRA Inc.)

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130, rue Slater St., Suite 405A, Ottawa, Ontario K1P 6E2. Tel. (613) 232-8811 Fax: (613) 230-9607
Email: csocme@istar.ca Website: http://home.istar.ca/~csocme/

Abstract

The main elements of this paper were presented by John Dyke at CSME's Sixth History Committee Seminar, held during the 1996 Annual Meeting at McMaster University. It draws together his many years of experience in the design of steam generators. The formal text of it was dated May 1996.

The paper begins with a 'revisit' of the early days of nuclear power generation in Canada. It then moves across the spectrum of nuclear steam generator design work done for specific projects, from NPD to CANDU 6. It also has a good deal to say about the way the design process 'works' and how the lessons of one application of a specific technology are applied to later applications. The relevant Figures all appear at the end of the paper.

About the Authors

John M. Dyke graduated from the University of Toronto in 1943 with a BASc degree in mechanical engineering. Following graduation, he joined the Royal Canadian Navy and reached the rank of Lieutenant (Engineer). During his service, he carried out research into the development of anti-acoustic torpedo devices at the Naval Research Establishment in Halifax. He later worked for CP Rail, Dominion Bridge, Babcock & Wilcox Canada (B&W) and Atomic Energy of Canada Limited (AECL). His association with nuclear steam generators and heat exchangers began at Dominion Bridge and continued through his career with B&W and AECL. He is now retired and lives in Cambridge, Ontario, and continues to do consulting work in nuclear engineering.

S. (Bob) Roy received his technical training in India and the UK. He completed an MSc degree in thermodynamics and related studies at the University of Birmingham. Since coming to Canada he has worked for AECL, B&W and the AGRA Engineering Group. He has participated in a number of task forces within AECL and Ontario Hydro, working on the resolution of problems in the performance and manufacture of nuclear steam generators. He is now a project manager at the Oakville office of Monenco AGRA and Canatom Inc.

About the Working Paper Series

In June 1991 the Board of Directors of CSME agreed that its History Committee should be responsible for the production of a series of Working Papers on topics related to the history of engineering generally and to the mechanical discipline in particular. These papers may or may not be authored by members of the Committee or the Society, but the opinions expressed will be those of the authors. The papers may also be published later, in whole or in part, in other vehicles; but this cannot be done without the expressed permission of the Canadian Society for Mechanical Engineering. The papers will have limited initial distribution, but CSME Headquarters in Ottawa will maintain a supply for distribution on request.

Preamble

The idea for this paper was conceived soon after John Dyke made a presentation on CANDU steam generators to the Huron-Niagara Section of the American Society of Mechanical Engineers in October 1995.

Dr. David Weaver of McMaster University persuaded him to record his 'personal view' of the evolution of the design of these generators. In parallel, plans were underway to commemorate the efforts of Thomas C. Keefer. Mr. Keefer was the designer of the Hamilton Water Works, and was the original promoter and also the president of the company that constructed them.

It appears that both the Water Works and the CANDU steam generators have a common heritage of steam technology in this region of Southern Ontario, as we have found out that Mrs. Patricia Dyke - John's wife - is a descendant of George Keefer, the father of Thomas. So there may be more than common geography tying these two technological events together!

Introduction

John Dyke has had a long association with the Canadian nuclear industry throughout his career at Dominion Bridge, Babcock & Wilcox and AECL, and much of it was spent in the area of steam generators and heat exchangers. This is a historical review paper, recording his views of the CANDU steam generator design evolution - starting from the days of the Nuclear Power Demonstration (NPD) to those of Darlington A station (1958-1980). This paper retraces the design evolution largely at Babcock & Wilcox (B&W) where he spent the majority of his time designing steam generators and leading projects of steam generator design and supply.(1)

The early days of Canadian nuclear energy generation are revisited, as are some of the background events leading to the decisions that are part and parcel of the evolution process. The initial CANDU steam generator designs were borrowed, developed by industry-wide competition, with modifications of existing designs tried in the next generations as part of this maturing process. We notice the same process was repeated for the components of this equipment - that is, a concept was adopted, was replaced because of the lessons learned, and then returned to with improvements made so that it would work finally in the way it was intended. The process of design, performance monitoring, and optimisation were very much a part of the learning curve in the development of CANDU steam generators. Although this process has seen many iterations, it is probably safe to say that it is alive and well today because steam generators continue to challenge both designers and operators by uncovering new complexities in the areas of materials and performance.

Co-author Bob Roy has had a long association with John Dyke in the field of nuclear steam generator engineering and is pleased to be a part of this historical review.

Early History of Nuclear Energy in Canada

In 1942 the majority of the personnel working on the military-related nuclear work in Britain were moved to Canada. We understand that the deciding consideration leading to Canada's agreement to host this group and their work was that, when peace returned, atomic energy would have applications of enormous social and economic significance and that the thrust of the research would be changed to bring this about.

In 1946, following the end of the Second World War, the Canadian Parliament redirected the nuclear program by passing the Atomic Energy Control Act. The Atomic Energy Control Board was established to oversee the use and development of atomic energy in Canada.

In 1952, a new Crown Corporation - Atomic Energy of Canada Limited (AECL) - was formed to continue the development of the peaceful uses of the atom begun by the National Research Council. The collaborative method of working with industry was established at the very beginning of the Canadian nuclear program. The first board of directors of AECL included senior utility industry representatives, one of whom was Richard L. Hearn, then chief engineer of the Ontario provincial utility. Ontario Hydro became interested in nuclear-generated electricity as an alternative to generating future capacity using costly (and potentially polluting) imported coal.

In 1953, AECL and Ontario Hydro proceeded with a feasibility study for a pilot nuclear power plant. The study team included industry representatives as well as AECL engineers. The leader was Harold Smith of Ontario Hydro, and John S. Foster of Montreal Engineering Company (a forerunner of Monenco AGRA) - a former navy colleague of John Dyke - was a member.

In 1954, the design and construction of a small demonstration plant with an electrical output of 20 MW was approved. This facility became known as the Nuclear Power Demonstration (NPD) plant - and the first CANDU, although the name itself had yet to be coined.

The Canadian and U.S. nuclear programs were by then proceeding in parallel, but the respective designs were developing a number of fundamental differences. These differences came about as a result of experience with the ZEEP and NRX reactors at Chalk River, as well as several important technical decisions made during the study and design phases of NPD, most importantly:

The reactor was to be moderated (and cooled) by heavy water.

The fuel originally selected was natural uranium rather than enriched uranium, because Canada had lots of the former but did not have any enrichment facilities. Later, uranium dioxide rather than uranium metal was chosen as the fuel. This decision translated into advantages for the CANDU system in terms of lower fuel costs and less environmental damage.

Zircalloy was chosen as the fuel cladding material.

In 1957, the reactor core design was converted from the vertical pressure vessel type to one with horizontal pressure tubes (and the facility was renamed NPD-2).

Seven companies were asked to submit design proposals for the complete plant. Canadian General Electric was the chosen bidder. The plant was built at Rolphton, Ontario, on the Ottawa River and began operating in 1962.

CANDU Steam Generator Design

NPD

Canadian industrial efforts to design nuclear steam generators did not begin with the NPD plant. For it, a U.S design was adopted. The design work was done entirely in the United States (by Babcock & Wilcox, at Shippingport, Pennsylvania), based on a U.S. Navy nuclear submarine application. Its main features were a horizontal U-tube bundle contained within a U-shell and a separate steam drum, as shown in Figure 1 (on page 10). This design established some important characteristics - such as the use of small diameter tubes and recirculating design - that are still trade marks of the current CANDU steam generators. The NPD generator was, however, manufactured at the Cambridge, Ontario, plant of Babcock-Wilcox and Goldie-McCulloch Ltd.

Douglas Point

NPD was followed by a prototype plant ten times larger, producing 200 MW for the Ontario grid. The CANDU name was first given to this plant, which was constructed at Douglas Point on the shores of Lake Huron.

For the steam generators, a design competition was held. Companies such as Babcock & Wilcox, Combustion Engineering, Montreal Locomotive Works and Dominion Bridge participated. Since the other companies had already developed vertical recirculating steam generator designs, Dominion Bridge offered an alternate design using forced circulation. This company had expertise in the design of Lamont-type forced circulation fossil fuel boilers and therefore thought it expedient to investigate, and offer, this design rather than a natural circulation arrangement. John Dyke was with Dominion Bridge at this time and was involved in the proposed design.

As a result of the competition, Combustion Engineering's design - as shown in Figure 2 - was selected, and it was further developed by AECL. The generators were manufactured by Montreal Locomotive Works, and the as-built design is shown in Figure 3. This design was also adopted for the first CANDU station in India (RAPP 1), and later in other CANDU stations in India.

The design had some similarities with that of NPD. It had U-tube bundles with U-shells, but they were vertical. One of the vertical legs had the preheating section, and the other one was the boiling section. A number of these 'hairpins' were connected to the horizontal drum. The concept behind the use of multiple hairpins was that any one of them could be replaced or isolated and repaired. These were recirculating-type generators with external downcomers.

The Douglas Point plant, being a prototype, suffered from 'teething' problems, but the steam generators operated without significant ones. There was, however, some fretting damage to the tubes due to vibration in the U-bend regions, and some tube wastage caused by phosphate in the boiling leg. But this plant and its steam generators served their purposes in bringing out design features not to be repeated in the next generation.

Pickering A

Ontario Hydro's Pickering A was the first large scale CANDU power plant. It was two-and-a-half times the size of Douglas Point, producing 500 MW (electrical) from each of its four units.

The bid document called for a repeat of the Douglas Point steam generator design. John Dyke was now working at Babcock & Wilcox and was appointed the nuclear steam generator proposal engineer. At this time, the steam generator operating experience in the European and U.S. pressurized water reactor (PWR) plants was becoming known through both the Chalk River Laboratories and Alliance Research (USA) of Babcock & Wilcox. The performance of the NPD-type design in the U.S. Navy was also becoming known by 'osmosis' over time. This information, combined with the technology of the time in regard to heat exchanger design using Monel 400 tubing and John's experience of tube cracking in the very short radius U-bends for the Douglas Point moisture separator and reheater (MSR), formed the basis for the Babcock & Wilcox alternative design for the Pickering A steam generators. This was different from the specified design in that there were no hairpins and the steam generator had an integral steam drum and an integral preheater at the bottom of the cold leg (light bulb type). According to the rules, the base bid still had to conform to the specification requirements - that is, the base bid went in as a repeat of the Douglas point design. The alternative proposed by Babcock & Wilcox was selected as the successful design. The Pickering A steam generator design is shown in Figure 4. All future stations except Bruce A adopted this concept. It may be noted that the steam generators for the KANUPP plant in Karachi, Pakistan, are also the light bulb type.

About this time the American Babcock & Wilcox company was involved in the supply of complete nuclear reactor systems and was offering a 'once-through' type of steam generator (OTSG) in the U.S. A policy decision was made that, in Canada, Babcock & Wilcox would concentrate on the design and supply of recirculating steam generators for CANDU plants, rather than becoming a reactor system vendor.

The design of the Pickering A generators saw the introduction of several innovative features, like low resistance tube bundle design by using lattice grid tube supports, as well as the use of relatively large U-bend radii (for the innermost rows) to avoid high residual stress and potential cracking (SCC). The choice of Monel 400 also proved to be a suitable tubing material for Pickering A's primary side conditions. The tubing material selection was based on this alloy's reliable operation in feed water heaters.

But the lattice grid type tube support did not stand up to the manufacturing process very well. The lattice bars were dislodged and a number of steam generators for the first two reactor units of Pickering A had to be repaired. The tube support design was strengthened and other changes were incorporated into the balance of the generators. This plant's generators have operated very well with only a handful (89 out of 124 800) of tubes being plugged due to manufacturing defects and operational degradation, and despite out-of-specification water chemistry during operation and outages, as well as the presence of a deep sludge pile on the tubesheet face.

Manufacturing experience influenced the steam generator design for the next generation of Ontario Hydro plants as well as the CANDU 6 plants. Starting with Bruce A, steam generators for Pickering B and Bruce B plants did not use lattice grid type tube support.

Bruce A

Each steam bank for this plant was designed to have four generators connected to a common steam drum. The arrangement is shown in Figure 5. Each reactor had eight generators in two banks. This appears to be a 'throw back' to the Douglas Point design. The common steam drum was chosen to simplify feed water control and provide a large inventory (storage) of hot water to act as a heat sink under postulated accident conditions. In operation, this design gave rise to high stresses at the junction of the drum and the steam generator under transients like heat-up and cool-down, due to the high stiffness of the entire assembly of the drum, generators and piping. The heat-up and cool-down rates were reduced to keep the stresses within allowable levels.

The tubing material was changed to Inconel 600 from Monel 400. This was done because the Bruce A reactor was designed with boiling in the reactor coolant (heavy water) in some of the fuel channels, and the steam generator tubes could 'see' reactor coolant with quality (vapour) in the hot leg. Under such conditions, Monel 400 has a significantly higher corrosion rate. This would translate into shorter tube life and, of course, a larger amount of irradiated corrosion product.

The design also moved away from integral to separate preheater vessels. There were four preheaters in each reactor unit. These heat exchangers also used vertical U-tubes, but they were oriented downwards rather than upwards, as in the steam generators. The preheaters heated the in-coming feed water to saturation temperature. A part of the reactor coolant flow passing through the steam generators was used in the preheaters.

There were two more important changes introduced to the steam generator component design. These related to tube supports in the straight legs and at the U-bends. Because the lattice grid design did not stand up to the manufacturing processes - that is, rotating, heat treatment, etc. - the tube support plates were made from solid carbon steel plates that had drilled and broached holes. The broaching gave a tri-lobar tube hole design with three small lands for supporting the tubes laterally, and extra flow area for steam and water mixture to pass through. This design did have a higher flow area than the plain drilled hole support plates and was thought to have less potential for the 'denting' phenomenon that later plagued the U.S. PWR steam generator tubes supported by carbon steel drilled hole support plates. ('Denting' is the name given to the processs of tube deformation in the support plates caused by the high volume of corrosion products from the carbon steel plates.) The drilled and broached support plates were definitely sturdier, but they had higher flow resistance and were more prone to blockages.

The U-bend supports were designed using 'scalloped bars.' A series of bars was assembled to form a plate and drilled to allow the tubes to pass through. The drilled holes were also coned. This was, in effect, a drilled hole tube support. The design proved to be inflexible and prevented the tubes sliding through the holes under operating conditions - as the design had intended - and especially as a result of corrosion product build-up due to off-specification water chemistry.

Bruce B

This plant, including the steam generators, was intended to be an exact repeat of the Bruce A plant. The operating experience of the Bruce A generators gave a strong incentive to all concerned to re-examine the common steam drum design. The industry, as well as the regulators (AECB), agreed to return to the integral steam drum configuration. AECL had recommended the design change to Ontario Hydro and John Dyke's response to AECB enguiries provided the manufacturing input. The redesigned steam generator and preheater arrangement is shown in Figure 6. The design retained the drilled and broached support plates. The design and manufacturing procedures were significantly modified for these vessels because of the tube damage discovered in the completed generators for the Pickering B station.

Pickering B

The steam generators for this plant had integral steam drum and preheaters like those of Pickering A. The tubing material was Monel 400, the same as for Pickering A - except that these were now ground to remove any surface defects. The tube support design was not lattice grid, but drilled and broached carbon steel support plates - the same as those for Bruce A. The Pickering B steam generators experienced tube damage during the vesssel's heat treatment procedure. This damage was first discovered in the generators that were already installed on site during eddy current testing to check for manufacturing defects. This is described in the following section.

CANDU 6

The design and manufacture of the steam generators for the CANDU 6 plants at Gentilly, Québec, Point Lepreau, New Brunswick, and Cordoba, Argentina, were in line with the design changes made following the Pickering A units (Figure 7). The tubing material was changed to Incoloy 800 because of the poor operating experience with mill-annealed Incoloy 600 tubing in the U.S. PWR recirculating steam generators. Other key components were very similar in design to those of the steam generators for the Ontario Hydro plants.

The generators for the three CANDU 6 stations also suffered similar damage to those for Pickering B during the same heat treatment procedure. Large temperature gradients dished the tube support plates and this caused tube damage. The Bruce B and Pickering B vessels were rebuilt at the B&W Cambridge plant, and the CANDU 6 generators were retubed on site prior to start-up. The rebuilding exercise involved extensive redesign of the key internals like preheaters, shrouds, U-bend supports etc. New manufacturing processes - some of them 'first of a kind' - were developed and used. AECL and Ontario Hydro staff involved in the projects participated in, and supported, these efforts.

The 'rebuild' project focussed attention at B & W on learning from past experience and developing steam generator designs and manufacturing processes that addressed the problems found during the operation of the generators. This marked a renewed effort in examining the design right from fundamentals, and involved external experts such as McMaster University's Dr. Weaver. Out of this effort emerged the new design for the Darlington A generators - and the new manufacturing methods. Design features like the low resistance 'egg crate' type tube support and the flat bar U-bend supports were reintroduced. Following Ontario Hydro's acceptance of the new design, AECL also approved the same changes for the generators for the later CANDU plants.

The same design and manufacturing elements were incorporated into the replacement generators for the U.S. PWR stations. The acceptance of the redesigned generators is clear from Babcock & Wilcox's success in supplying replacement generators for a number of PWR stations.

Conclusion

CANDU steam generator design has come a long way since the early days of nuclear energy development. The process that started with the adoption of a U.S. design has charted its own course over the years. Characteristics such as low resistance, high circulation tube bundle design, smaller tube diameter, and smaller overall size are the most noteworthy features. The tube performance of the CANDU generators has far exceeded that for the pressurized light water reactors, albeit that the PWRs have higher operating temperatures.

The detailed design development was carried out by Babcock & Wilcox. AECL's development work was in the areas of materials and performance, and also contributed significantly.

John Dyke had his longest association with the CANDU steam generators at Babcock & Wilcox, where he led the effort for Pickering A and a number of subsequent CANDU units. He would describe his experience as a learning process - all the way from childhood and through his early experience years in the Royal Canadian Navy. His favourite phrase in this regard - 'Chance favours the mind which is prepared' - seems to summarize it most aptly.

*****

Reference

A Short History of the CANDU Nuclear Power System, by G.L. Brooks, published by AECL (#10788).

Figures

All of these were hand sketched by John Dyke, and were scanned into his computer without enhancements. The first seven correspond to the Figures cited in the text. The eighth is a composite drawn in March 1995 that shows the evolution of the design.

Note

(1) The name of the Canadian Babcock & Wilcox company was - from 1923 until 1967 - Babcock-Wilcox and Goldie-McCulloch Limited. Both have usually been referred to in the text simply as Babcock & Wilcox. The story of the Canadian company has been told in the book Babcock & Wilcox Canada: A History 1844-1977, published by the B&W head office in Cambridge, Ontario. An essay based on this book was included in the CSME's 25th Anniversary Commemorative Volume, From Steam to Space.... This Dyke-Roy Working Paper may also be considered a companion for the three essays on CANDU components and materials by Philip Ross-Ross that appeared in the Commemorative Volume.

List of Figures

Figure 1

Steam Generator for NPD

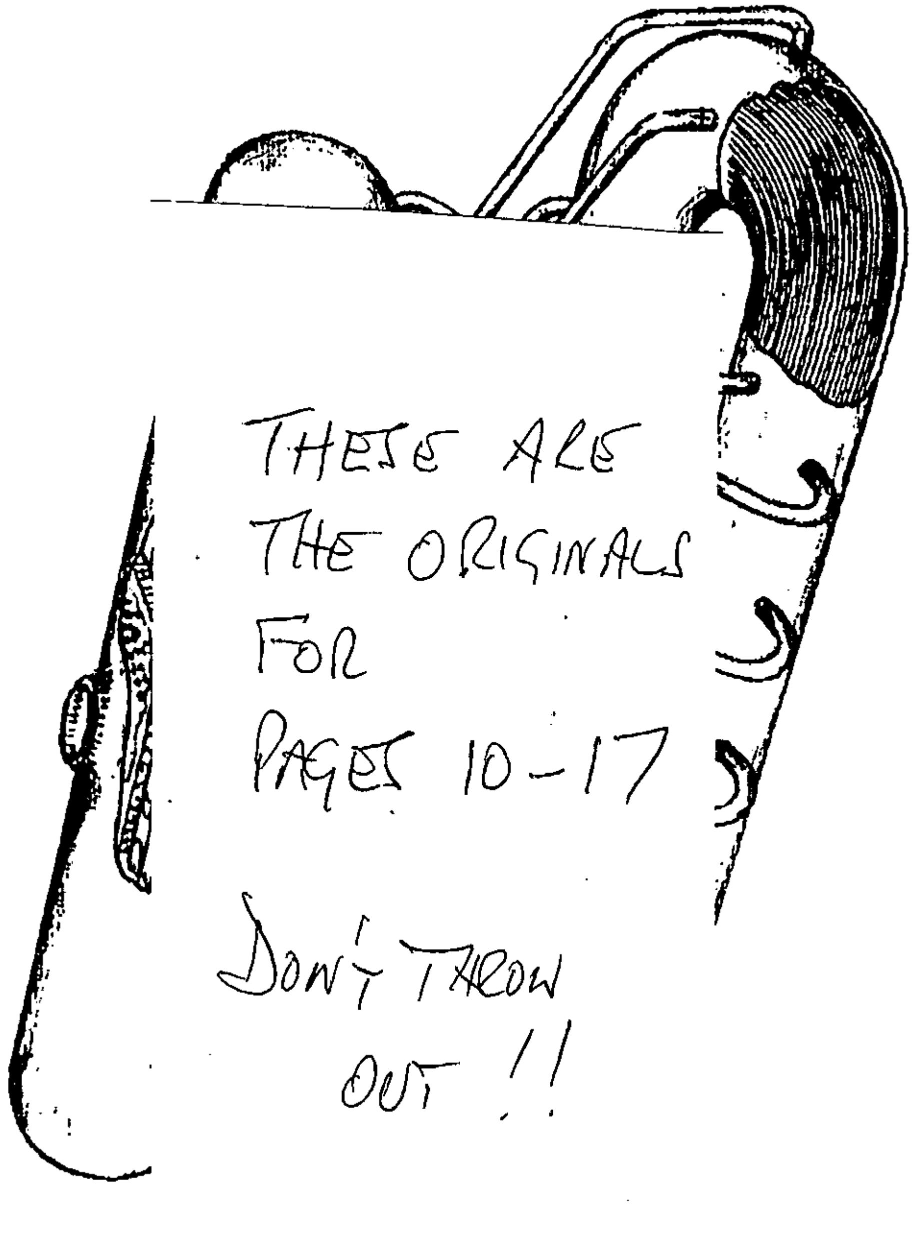

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Figure 2

The Winning Design for Douglas Point by CE

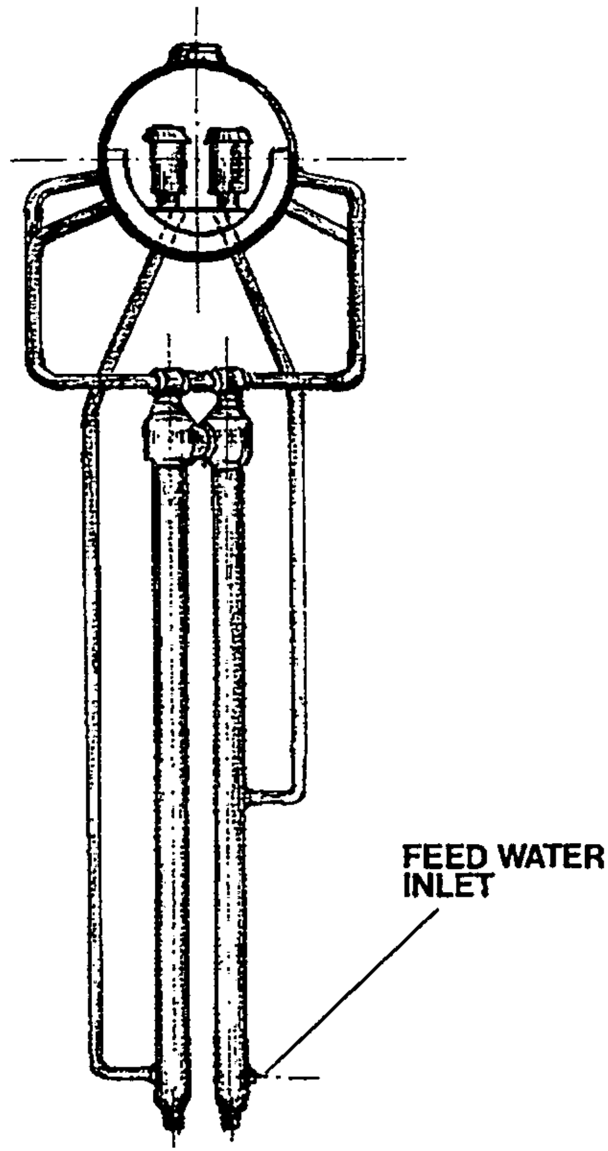

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Figure 3

A.E.C.L. Design for Douglas Point

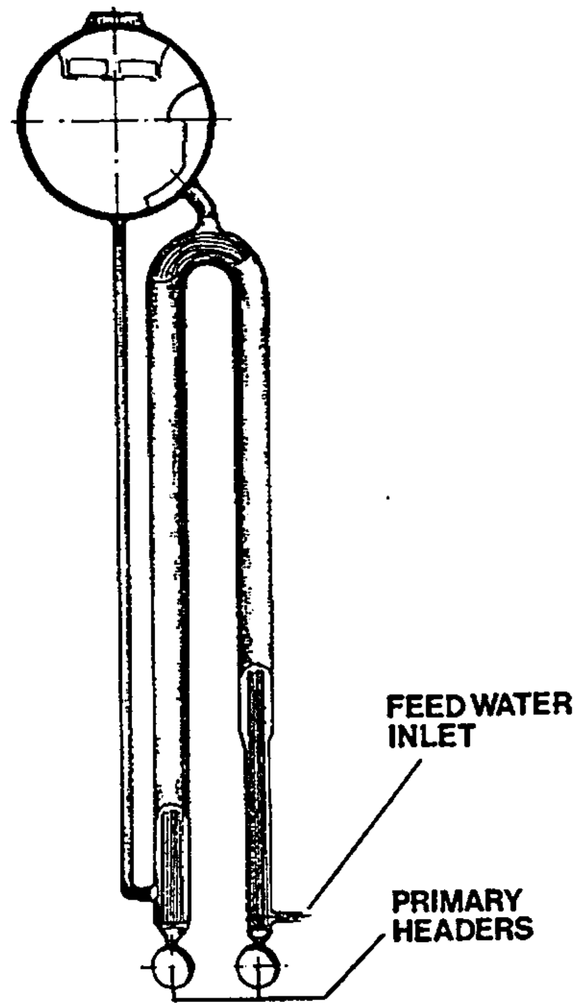


Figure 4

Pickering A Steam Generator

Figure 5

Bruce A Steam Generator & Preheaters

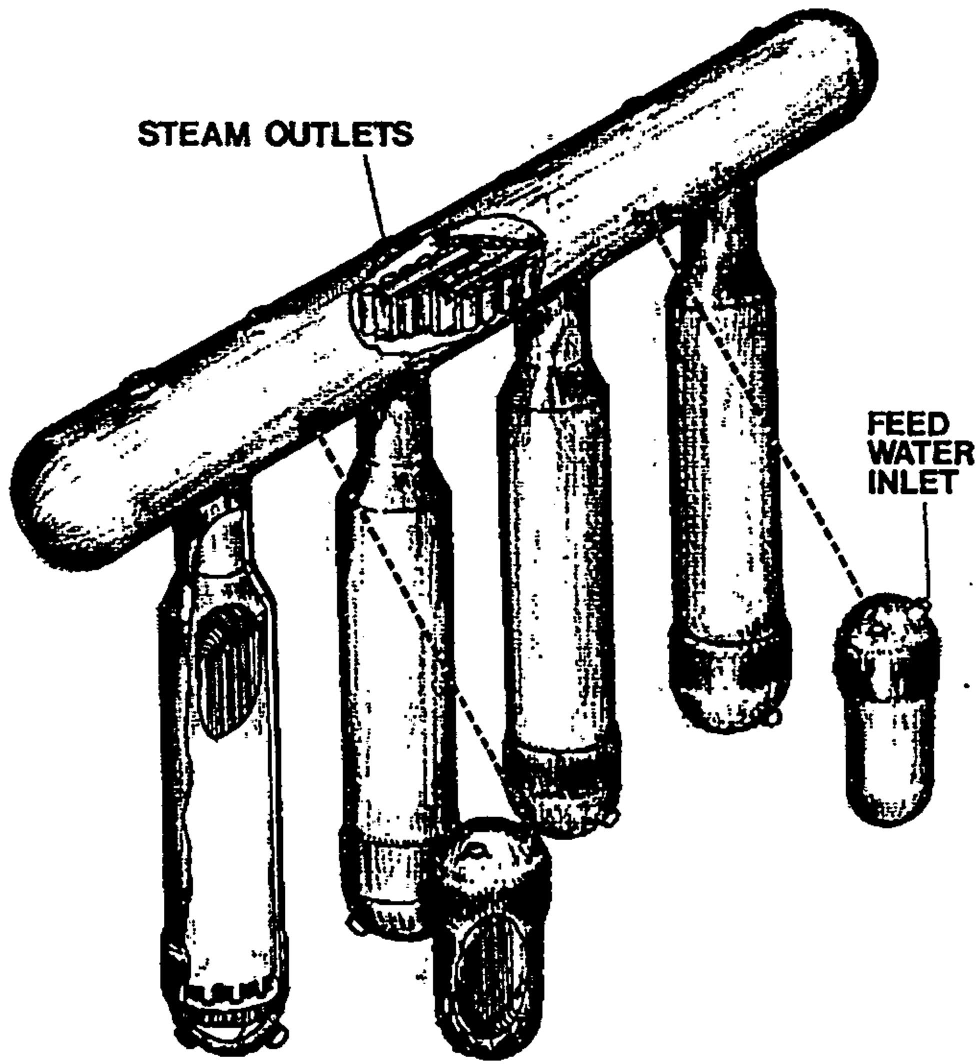


Figure 6

Ontario Hydro Bruce B

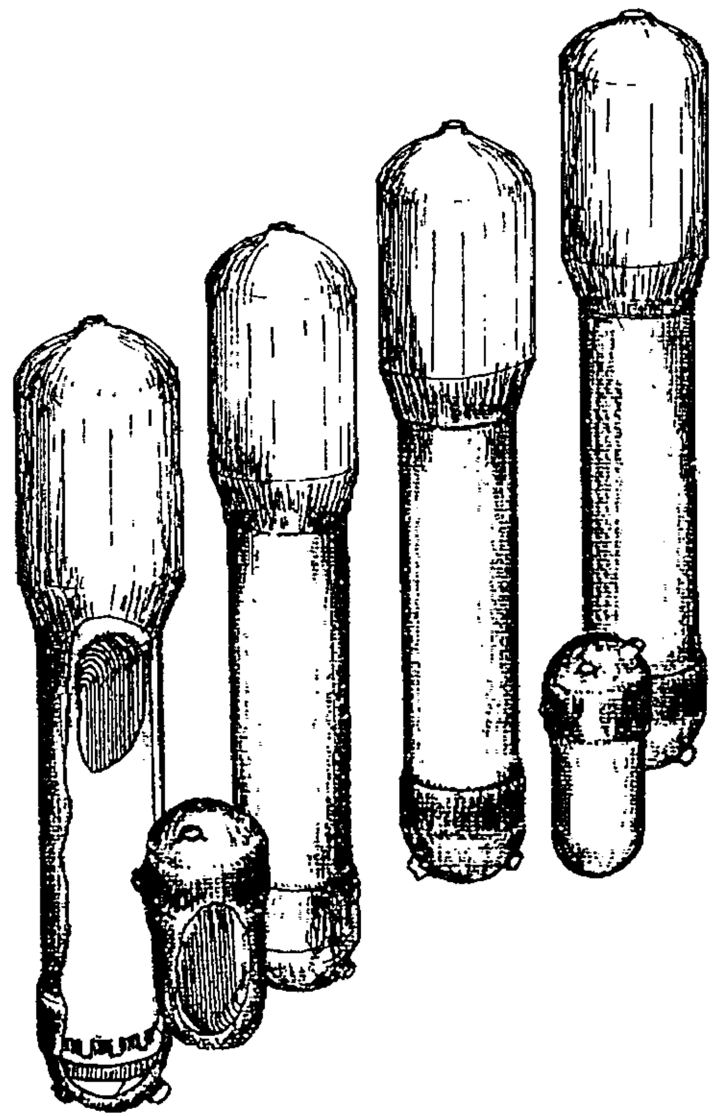


Figure 7

CANDU 6 Steam Generator for Gentilly 2

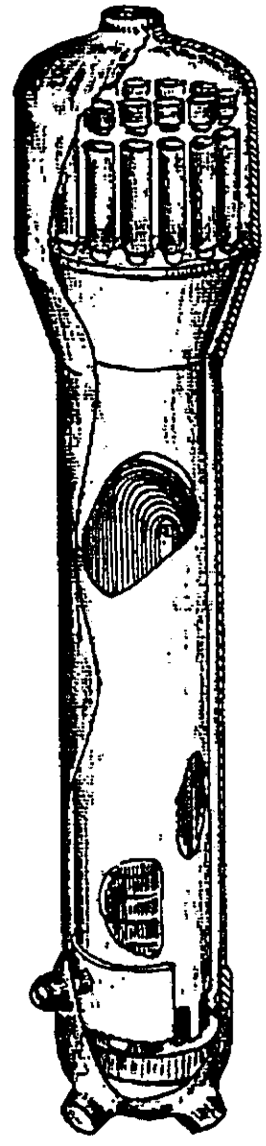
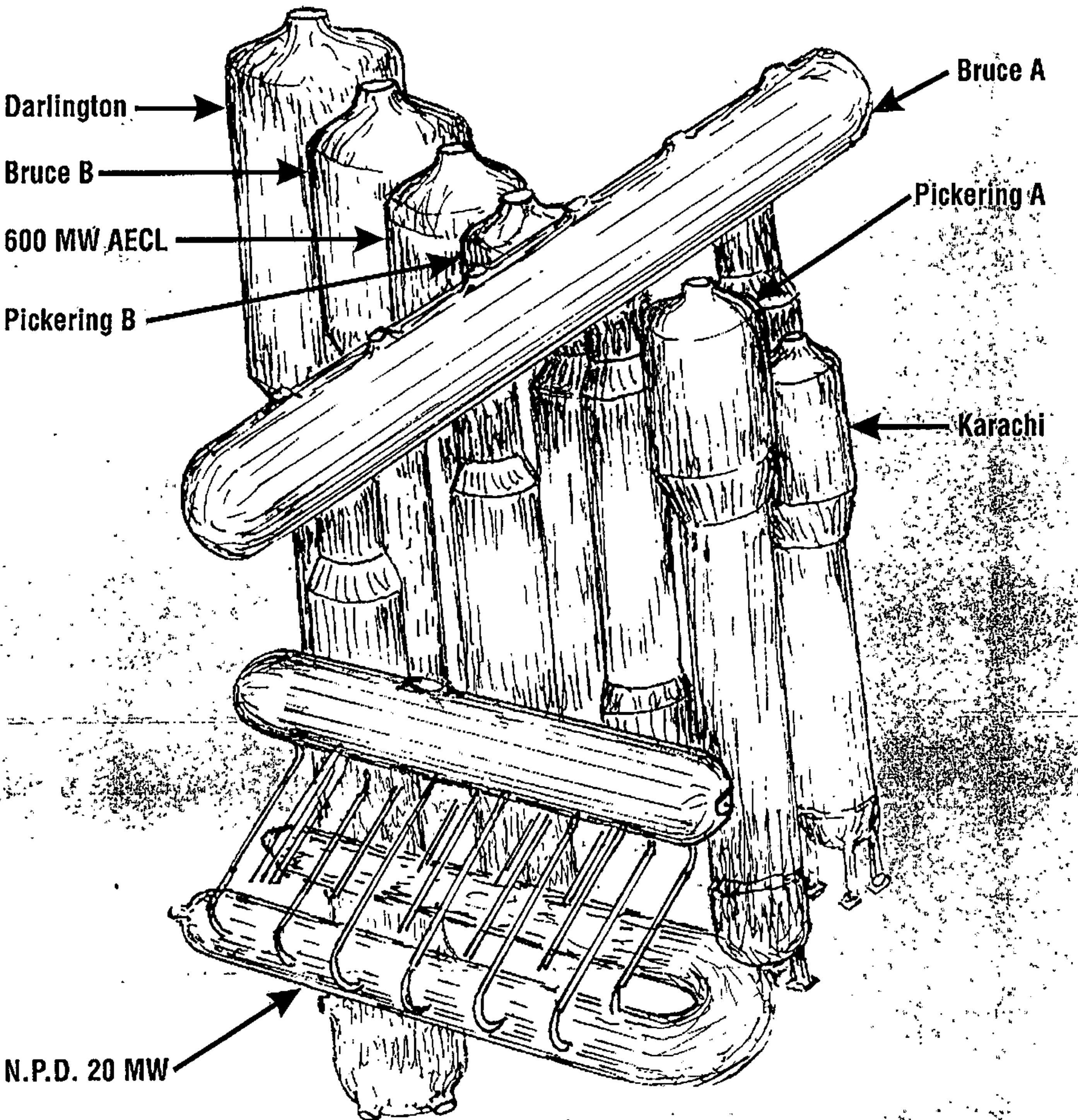


FIGURE 8

Evolution of CANDU Steam Generator Design
Babcock-Wilcox Canada 1958-1980



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