EMERGENCY CORE COOLING STRAINERS – THE CANDU EXPERIENCE

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Summary

The Canadian nuclear industry, including Atomic Energy of Canada Limited (AECL) and the four nuclear utilities (New Brunswick Power, Hydro-Québec, Ontario Power Generation and Bruce Power) have been heavily involved in strainer clogging issues since the late 1990s. A substantial knowledge base has been obtained with support from various organisations, including the CANDU Owners Group (COG), AECL and the CANDU utilities. Work has included debris assessments at specific stations, debris characterisation, transport, head loss measurements across strainers, head loss models and investigations into paints and coatings. Much of this work was performed at AECL's Chalk River Laboratories and has been used to customise strainer solutions for several CANDU (PWR-type) stations. This paper summarises the CANDU experience, describing problems encountered and lessons learned from strainer implementation at stations.

Between 1999 and 2003, AECL supplied strainers to six different CANDU stations, representing 12 units with a total power output of approximately 8.2 GWe. Each station had unique needs with respect to layout, effective area, allowable head loss and installation schedule. Challenges at various sites included installation in a covered trench with single-point access, allowing for field adjustments to accommodate large variations in floor level and pump suction location, on-power installation, very high levels of particulate relative to fibrous debris, and relatively low allowable head loss.

The following are key points to consider during any station assessment or strainer implementation:

- a realistic testing model and method is essential for accurate predictions of head loss, and the limits of the model must be understood;
- assessment of station debris must be sufficiently conservative to overcome uncertainties in debris generation and transport models;
- appropriate and reliable data (e.g. flow rate, layout, size of test model, method of debris generation and deposition, test duration), with true representation of the various field conditions, is necessary to select the appropriate strainer solution;

- flexibility in the strainer design permits adaptability to different plant layouts and schedules, while maintaining basic design qualification;
- innovative header design can improve strainer efficiency;
- reducing the strainer footprint-to-surface area ratio is desired; and
- detailed review of specific station layout is critical prior to final design, fabrication and installation.

The experience attained in Canada shows that practical solutions for strainer issues can be developed to meet a wide range of needs. However, diligence is required to ensure that the solution has adequate (but not undue) conservatism to accommodate uncertainties, that station-specific design issues are properly addressed, and that the installation schedule for new strainers is suitable. Interaction with the regulator early in the project also helps to bring any outstanding issues to the forefront when there is still sufficient time to make adjustments, and to facilitate subsequent approval.

Background

Following the Barsebäck incident in Sweden, Canadian nuclear stations and Atomic Energy of Canada Limited (AECL) began assessing the current status of emergency core cooling (ECC) systems in Canadian and off-shore CANDU stations. Early on, it was recognised that the available information was inadequate to address CANDU needs, and a research programme was developed. This research, carried out primarily at AECL's Chalk River Laboratories, with various funding sources, focussed on characterising the head loss across a strainer as a function of a multitude of variables. These variables were selected to encompass CANDU station configurations and included type and quantity of fibrous and non-fibrous debris, water temperature, pH, flow rate, strainer configuration, debris generation and deposition, and test duration, among others. As the database expanded, the validity of an existing correlation was evaluated for its applicability to the conditions tested. When it was found not to provide acceptable agreement, a new correlation was developed for specific CANDU-type applications.

Concurrently, in consultation with the Canadian Nuclear Safety Commission (CNSC), the utilities began to evaluate the suitability of their existing ECC systems. These evaluations included debris assessments within the reactor building, and analyses of accident scenarios. In its role as reactor designer, AECL assisted off-shore CANDU stations in similar tasks. Eventually, stations were ready to proceed towards a solution that would satisfy the regulator (CNSC). Typically, the solution involved a combination of strainer replacement and some debris replacement. Interaction with the regulator continued throughout the process to ensure compliance. Most stations have now completed, or are near the end of, their strainer programmes and have satisfied the regulator that their ECC system configuration now meets safety requirements.

Testing

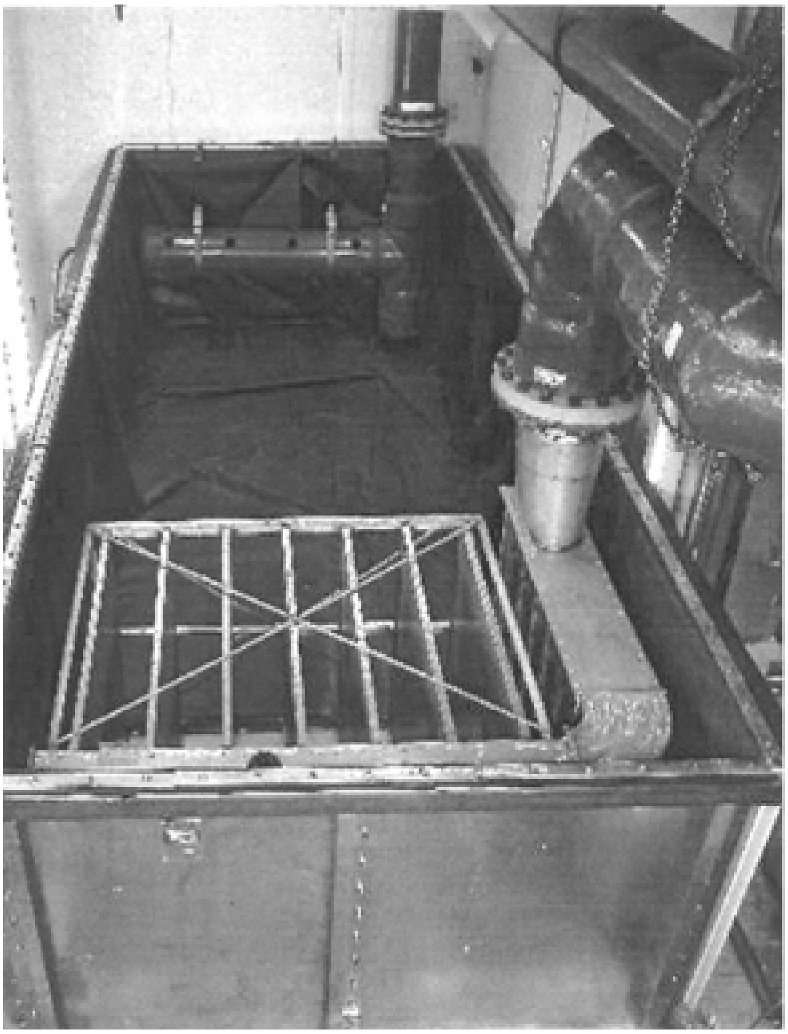
Considerable effort has been expended in Canada to characterise and quantify debris that may reach the ECC strainers. A large portion of this work was funded through the CANDU Owners Group (COG), a body representing CANDU station owners and developers. The results of walkdowns at stations were used as a starting point. Similar debris to what was found in the stations was obtained for the testing. Visual examination, including scanning electron microscope (SEM) imaging, was performed early on to provide a baseline. A variety of small-scale tests were then performed in several different facilities at Chalk River Laboratories. These included measuring material strength and density, the deposition rate of particulate and fibrous debris, the effect of temperature on the material structure, and the effect of particulate size on generic clogging. In addition, several bench-top flow loops were set up to observe flow passage through a strainer. A significant amount of information was generated and served to direct future testing.

A medium-scale test facility was then built for more rigorous testing. This is a Jacuzzi-sized tank with piping to connect to a pump. A stirring device in the rig allows debris to mix, while a heater/chiller maintains the desired water temperature. The strainer surface filters the debris as the water flow passes through it. Any debris passing through the strainer can be caught in a downstream trap if desired, and a heat exchanger scaled to CANDU size can be piped in. The downstream components can be used to evaluate different hole sizes in the perforated metal in terms of plugging downstream components. The strainer surface area and orientation can be adjusted in the rig. The rig is fully instrumented and includes flow and temperature control. Over one hundred and fifty tests have been performed in this facility, ranging in duration from a less than an hour to three months. Figure 1 shows the medium-scale facility.

Figure 1. Medium-scale facility

A large-scale facility is also available. This facility was commissioned for development of AECL's *Finned Strainer*® product. It accommodates one complete *Finned Strainer* module, which, depending on the application typically has 20-33 m^2 available straining surface area. It consists of a large lined tank (approximately 1.5 m deep, 2.5 m wide and 5 m long) connected to a large piping system. Temperatures, pressure drop across the strainer, test duration and flow rate are monitored during testing. Figure 2 shows the large-scale facility.

Figure 2. Large-scale test facility



Development testing using the large-scale facility included testing fibrous and particulate debris, as well as the ability of the strainer to accommodate large debris such as rubber gloves, plastic bags, etc. Extensive vortex testing was also performed. In these tests, the flow rate, water level above the strainer, pressure drop and debris loading were all investigated to determine their effect on the formation of hollow-core vortices, which could result in air ingestion and pump damage.

The large-scale facility was also used to confirm the performance of each strainer supplied to a customer.

Finned Strainer® is a registered trademark of AECL.

Vortex testing

Of considerable concern for the CANDU utilities was the potential for the formation of hollow core vortices. With a large pressure drop across the strainer, stations needed assurance that air ingestion due to vortices was not possible. A number of tests were performed in which the submergence of the strainer (the distance between the water surface and the upper-most straining area) was fixed and the flow rate was varied to see if a vortex would form. This was done for several difference submergence levels and debris loading conditions. Table 1 shows the results of one set of tests, which forced the flow through a much smaller section (~90 mm wide) of the strainer than would normally be expected. This test simulated the effect of the flow concentrating at the screen nearest the pump intake. This could only happen when there is no debris on the strainer; once debris builds up, the extra resistance distributes flow to the whole screen area, effectively reducing the likelihood of vortices.

Table 1. Vortex test results*

Flow (L/s)	Submergence (mm)	Pressure drop (kPa)		Hollow core vortex?
150	450	28	(some debris)	No
100	375	7	(clean)	No
75	375	3	(clean)	No
75	300	3	(clean)	Yes (3 mm dia core)
55	300	1	(clean)	No
55	225	1	(clean)	Yes (occasional, 3 mm diameter core)

* The strainer area was not identical for each test.

The results of the vortex tests were used to refine the strainer design for a given station, either by adjusting the submergence or the surface area to prevent flow concentration that could cause vortexing.

Head loss correlation

A head loss correlation available publicly was evaluated for use in CANDU applications. However, as the test database expanded, it became clear that this correlation was not suitable for CANDU. A new correlation was then developed, based on the tests performed. However, even this correlation was found to be limited in its range of applicability. For instance, a high particulate-to-fibre volume ratio was found to result in significantly higher head loss than predicted. The development of the correlation highlighted the uncertainties in many of the parameters (e.g. materials, order of deposition on the strainer) and the need to perform rigorous testing for each customer in a large-scale facility.

Debris

The debris types common to CANDU stations include fibrous debris (fibreglass), calcium silicate, marinite (a dense form of calcium silicate), rust, dust, dirt and paints (coatings). Samples of these were obtained from stations and from commercial suppliers, using the same suppliers as the stations where possible.

Fibrous debris was photographed using SEM imaging. Fibre diameters from different sources were compared. For head loss testing, a leaf shredder was used to break the fibrous debris into smaller pieces. The fibrous debris was then soaked prior to insertion in the test tank, as the debris reaching the strainer in CANDU stations would also be wet.

Calcium silicate was broken up using an impact hammer. A variety of screen sizes could be used with the hammer mill to affect the resulting particulate size distribution. The effect of the different sizes was evaluated in the testing. Other experiments were performed to determine the rate of erosion of calcium silicate pieces exposed to flowing water. Of concern was whether significant debris could be generated by erosion of large pieces of material that fall into the flow during an accident but are not transported to the strainer. Significant erosion of large chunks of material could lead to delayed deposition of calcium silicate on the strainer, which could lead to different results than for a fully-mixed debris bed.

Iron oxide of two different particulate size distributions was purchased to represent rust.

Paint chips were prepared at Chalk River Laboratories and added to the debris mixture for the tests. In addition, a detailed test program was performed to evaluate the performance of paints and coatings typically used in CANDU stations under accident scenarios. The intent of this testing was to determine if, during an accident, the coatings would be likely to degrade to a degree that could impact strainer performance. This testing involved irradiation, exposure to high-temperature, high pressure transients, and long-term exposure to post-accident conditions. Tensile and adhesion tests were performed periodically.

Relevant accident scenarios for CANDU stations

CANDU stations are a subset of pressurised water reactors (PWRs). In these reactors, heat from the reactor is transported by means of high temperature, high pressure heavy water in the primary heat transport system (PHTS) to a steam generator. The energy is then transferred to light water in the steam generator for driving the turbine.

In the PHTS, the main coolant pumps force water into headers, from which multiple small feeder tubes (between 380 and 480, depending on the station) pass through the reactor core and regroup in another header on the other side (Figure 3). From here, the water passes through a steam generator before re-entering the PHTS pump. The feeders are located in an insulated “feeder cabinet”. A break in any of the PHTS piping is considered a loss of coolant accident (LOCA). In a CANDU 6 station, such an accident triggers a high-pressure injection system, in which pressurised water is injected into the PHTS, and a dousing system sprays cool water into containment to reduce the pressure. This is followed by medium-pressure injection, consisting of emptying a large tank of water, located in the reactor building ceiling, into the system. The water added during high- and medium-pressure injection eventually leaks out of the break in the PHTS and fills the reactor building sump to a level sufficient to initiate the low-pressure injection system. When this system is operating, the basement water is filtered through a strainer prior to passing through the ECC pumps, heat exchangers and back into the PHTS to provide continued cooling to the reactor core. The low-pressure injection mission period is typically three months. Figure 4 shows the high-, medium- and low-pressure injection systems for the CANDU 6 station.

Multiple-unit CANDU stations have a single “vacuum building” connected to all four units that prevents pressure build-up during a LOCA, instead of the dousing system used in CANDU 6 station. Water for high-pressure injection is contained in a large storage tank. Low-pressure injection is similar to that described above, except that for Darlington, all four units share the same strainer. Figure 5 shows a schematic of the system.

Figure 3. CANDU 6 header and feeder arrangement

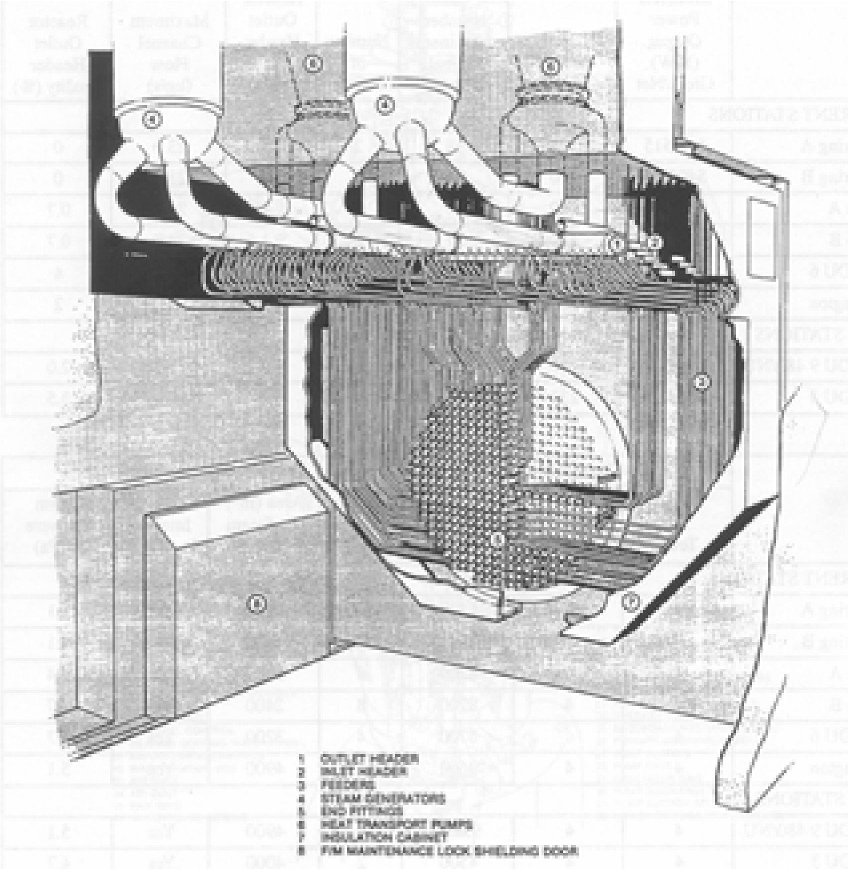


Figure 4. CANDU 6 emergency core cooling system

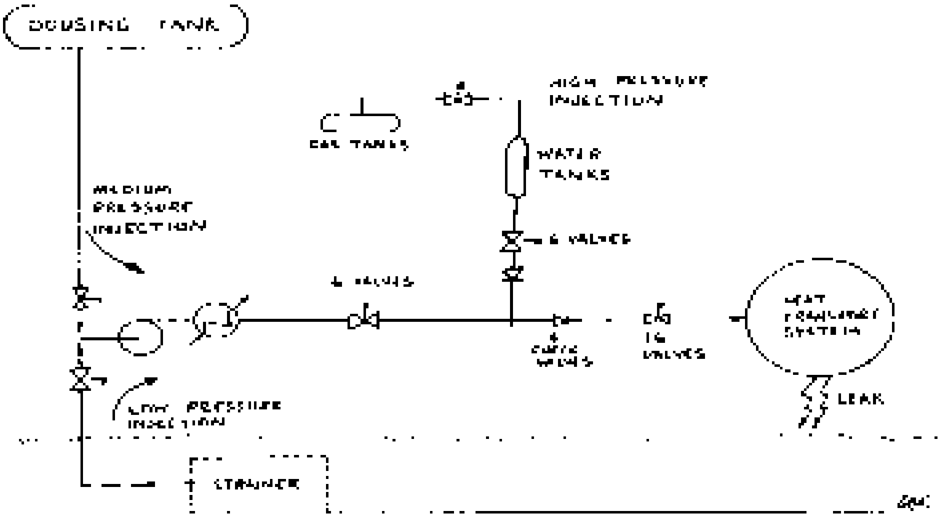
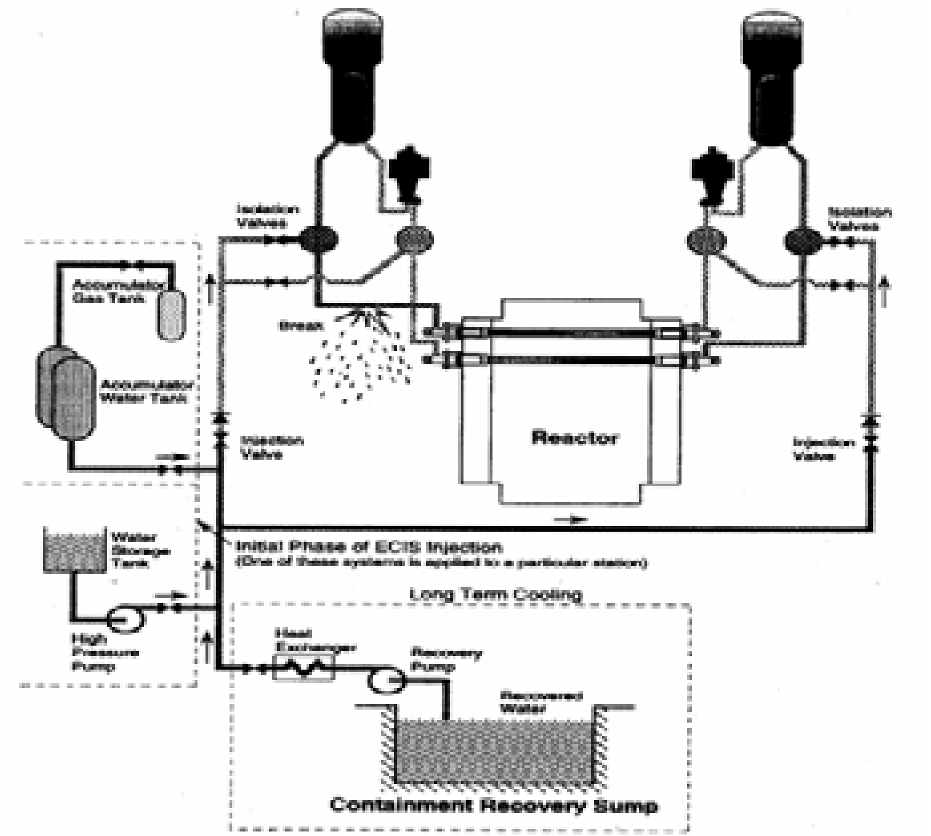


Figure 5. Typical multi-unit CANDU emergency core injection system



One of the main postulated sources of debris is from the feeder cabinet. A break in any of the feeders could result in a jet of high temperature, high pressure water impacting upon the insulation in the feeder cabinet, liberating large amounts of material which then could flow towards the sump. Other debris from this and other rooms along the way, such as fibreglass or calcium silicate insulation, dust, paint flakes, rust, or loose trash could also get transported to the sump. All this debris must be filtered by the strainer.

A break in the header or the large piping may occur in a variety of areas and sizes, each scenario liberating a different amount and type of material. Thus a multitude of possibilities must be assessed.

Failure of the strainer by clogging could cause the ECC pump(s) to cavitate, potentially leading to insufficient heat removal from the reactor core. Failure of the strainer by debris passage (e.g. due to large perforations or partial collapse) could result in damage to the ECC pumps, clogging of heat exchangers or clogging of pressure tubes in the reactor core. All of these could lead to unacceptable heat build-up in the reactor core.

Customer needs

While the background research was in progress, stations performed assessments of their ECC systems to determine requirements for any upgrades. A key part of this task was the debris assessment, in which every room in which water could flow during a LOCA was examined to determine the type and amount of debris that could become dislodged and could potentially travel to the ECC sump. Assessments were made for all applicable scenarios.

Based on the above assessment, strainer requirements were defined. The existing strainer(s) was then evaluated against these requirements. In most cases, deficiencies were noted and upgrading the strainer was initiated, based on the identified needs, available space and other restrictions.

The CANDU stations that have chosen to meet their regulatory requirements by upgrading their strainers are shown in Table 2.

Table 2. Upgraded strainers at CANDU stations

Station	Rated flow (L/s)	Old surface area (m^2)	New surface area (m^2)	Old footprint (m^2)	New footprint (m^2)	Number of ECC strainers per unit
Point Lepreau	606	6	79	1.1	12	2[a]
Gentilly-2	606	6	100	1.1	14	2[a]
Pickering A (four units)	340	~4	~64	~2	~7	2
Pickering B (four units)	707	4	110	~3	22	1
Embalse[c]	625	6	100	1.1	15	1[b]
Cernavoda 1[d]	625	6	79	1.1	12	2[a]
Darlington (4 units)	2 190	~10	1 200	~6	70	1[e]

[a] One 100% capacity strainer per pump, only one pump is used at a time (two pumps total).

[b] Two pumps connected to one 100% capacity strainer, only one pump typically operating at a time.

[c] This station is located in Argentina.

[d] This station is located in Romania.

[e] Single strainer is connected to all four units.

For the CANDU stations listed above, models generally predict that approximately 10 m^3 of fibrous debris and lesser quantities of other debris types may reach the strainer, although the amounts vary depending on the break size, location and the particular station's debris types. In some plants, the quantity of calcium silicate pipe insulation that could reach the strainers has been a concern, so measures are being taken to remove or protect some of this material, and to prevent its use in new plants.

The *Finned Strainer*® units designed and manufactured by Atomic Energy of Canada Limited for retrofit into these stations are very compact, allowing a large surface area for filtering to be installed in a small space, which allows them to fit into crowded plants. They are also modular, allowing flexibility in the layout and size.

Utility/supplier interactions

During the early testing period, a close working relationship was developed between the utilities and AECL. The utilities had a large input into the test programs and, in many cases, visited AECL to view the test facilities. These close relationships were maintained during the commercial contracts, which overlapped the background test period. In fact, the schedule or even scope of the COG-funded background testing was sometimes revised to suit the utilities' immediate strainer retrofit issues, provided that all other COG members agreed to the change. In this way, the utilities gained confidence in AECL's capabilities, and AECL had the flexibility to address utility concerns quickly.

The high level of communication between supplier and client ensured a full understanding by AECL of the layout restrictions, installation schedule and operating sequence for each station. Detailed knowledge of layout restrictions was particularly important at Pickering B. In this four-unit station, the strainer was to be located in a covered trench, approximately 50 feet long, 4 feet deep and 4 feet wide, with a small opening at one end. The size of the trench limited the size of the strainer. Installation was also extremely challenging, due to the confined area and the necessity to work in plastics. Because the trench cover was permanent, the strainer had to be lowered in modules into one end of the trench. Typically, each module consisted of a section of header, several perforated fins (which provide the bulk of the straining area) and bracing. The strainer is shown in Figure 6. A "railroad track" was built on the bottom of the trench and each module was rolled on the track along the trench until it butted up against the preceding module. Modules were fastened together in order until the entire strainer had been assembled. A mock-up of the trench was fabricated at site to provide training for personnel prior to assembly in the real trench. This was an important means of preventing difficulties during on-site assembly.

All strainers supplied to the utilities were pre-assembled at AECL to test all hardware prior to arrival at site. Station personnel were invited to Chalk River Laboratories to witness strainer fabrication in the sheet metal shop and to become familiar with the equipment prior to installation at site. Not only was this an important training opportunity for station personnel, their feedback was needed to ensure that installation issues were resolved before the equipment arrived at site. This proved exceedingly valuable. The pre-assembly was also useful to verify the steps in the operating manual, and was key to the smooth assembly of each strainer at site. Figure 7 shows a typical CANDU 6 strainer installed at site.

The Darlington NGS strainer replacement project was also challenging. The first major issue was the large quantity of particulate debris (originating from calcium silicate insulation). This necessitated a very large strainer, shown in Figure 8, having over ten times the surface area at other CANDU plants. The other major issue was the desire to install the unit while at power. To achieve this, the strainer was installed on top of the existing sump grating, and used the existing grating as part of the structure of the new strainer. As it turned out, the installation was completed very smoothly and ahead of schedule, leaving all parties very pleased with the outcome.

Minimising the footprint for a given required strainer surface area was a key requirement for each station. At Embalse, this was complicated by the existence of a non-structural 'L'-shaped wall separating the two sump inlets. Although a single strainer joining both sumps was desired, removal of the wall would extend the outage time to an unacceptable duration. Eventually, a complete reconfiguration of the initially-accepted layout was proposed, in which the strainer snakes around the end of the wall and doubles back to connect to both suction pipes. This option was accepted and resulted in a much shorter installation time and reduced costs because the wall could be left as is. A further challenge for this project was to ensure that the design had sufficient flexibility to accommodate the measurement uncertainties in the location of the suction pipe inlets and in the elevation of the basement floor where the strainer was installed. A trip to the site to inspect the strainer area, clarify the requirements, and identify customer needs and wishes was key to the success of this project.

Figure 6. Pickering B *Finned Strainer* pre-assembled at AECL shop (top) and installed in covered trench at Pickering (bottom)

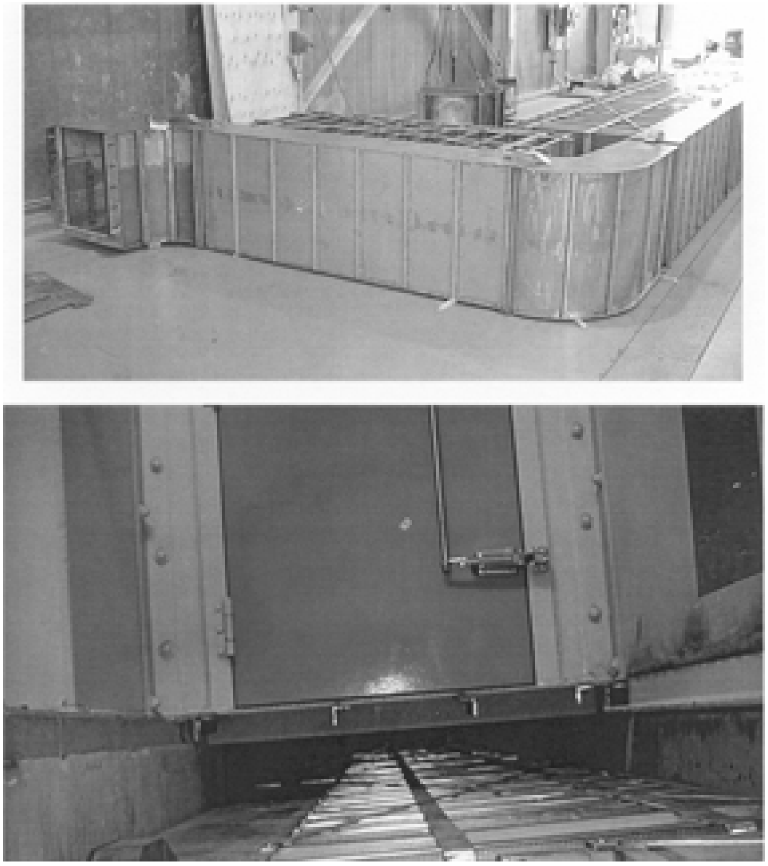


Figure 7. Typical CANDU 6 *Finned Strainer*

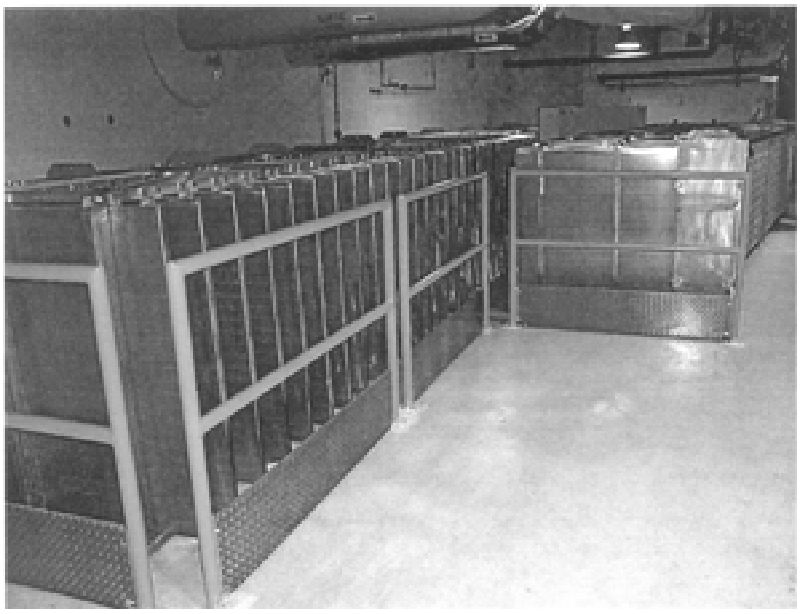
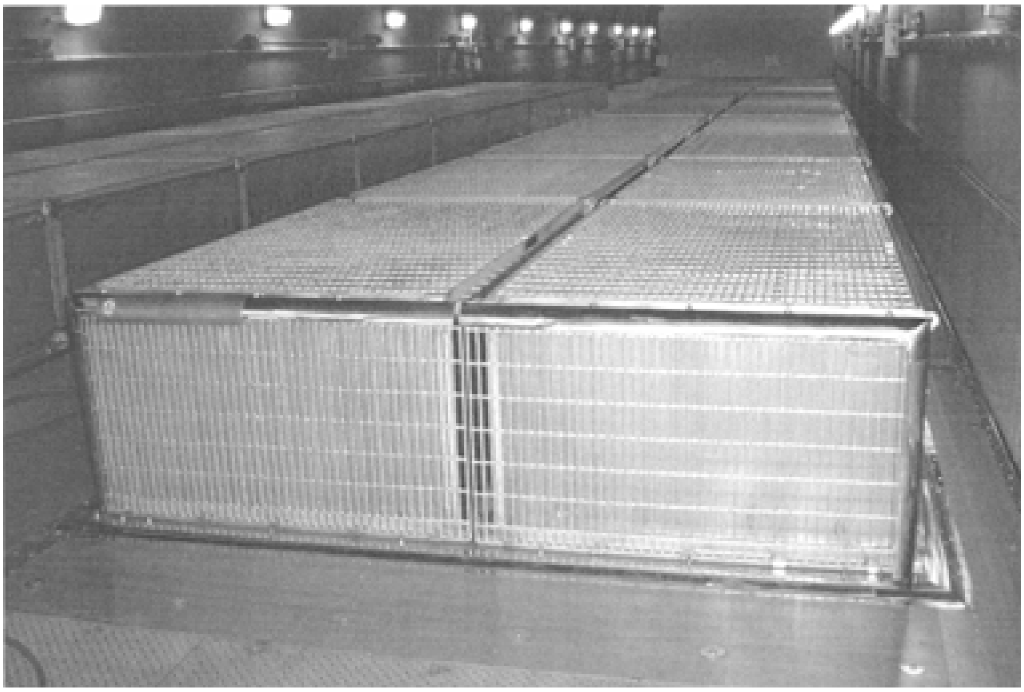


Figure 8. Darlington NGS *Finned Strainer*



Large-scale testing

Each strainer supplied by AECL was originally sized and configured based on the background test results. In addition, station-specific tests were conducted in the large-scale facility to confirm that the strainer met the head loss requirements stipulated by the customer. To qualify a strainer for its intended use, one full-scale module was placed in the tank and connected to the piping system. If the module represented 1/5th of the total strainer surface area to be supplied to the customer, then 1/5th of the full-scale debris was prepared for the test. As with the debris, the flow rate was scaled based on the ratio of full-scale surface area to test surface area in order to obtain the desired approach velocity. The temperature was set to the predicted station value. Once the tank was filled, the pump was started and debris was added. All relevant parameters were monitored throughout the test. The test report provided to the customer was later used by them to satisfy the regulator that the strainer was fully qualified.

Regulator interactions

For the Canadian utilities, acceptance of their proposed strainer solutions by the CNSC was required. This was facilitated because the CNSC had some previous exposure to the head loss testing being performed at AECL. By maintaining an open relationship with the regulator, AECL was able to understand their concerns and ensure that these were addressed in the strainer testing and design. Thus when final submissions to the CNSC were prepared by the stations, there were no last-minute issues to cause delays and concerns. In fact, Gentilly 2 asked AECL to attend their meeting with the regulator to make the presentation on their behalf.

Summary

A large body of knowledge relating to emergency core cooling strainers exists in Canada. This knowledge has been acquired through the co-operation of many parties, including utilities, strainer designers and COG. A great deal of cooperation and communication between utilities, designers and the regulator existed throughout the research, development and supply phases. This has permitted the knowledge to be utilised to provide effective solutions to CANDU ECC strainer issues. Stations are nearing the end of their ECC strainer programs and the industry is looking to move on to other challenges.

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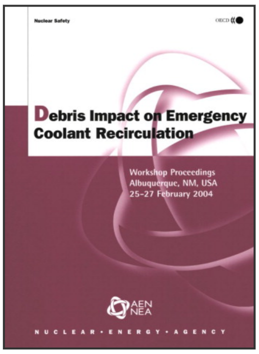

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Eyvindson, A., *et al.* (2004), “Emergency Core Cooling Strainers – The CANDU Experience”, in OECD/ Nuclear Energy Agency, *Debris Impact on Emergency Coolant Recirculation: Workshop Proceedings, Albuquerque NM, USA, 25-27 February 2004*, OECD Publishing, Paris.

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