

STEAM GENERATOR CLEANING CAMPAIGNS AT BRUCE A: 1993 – 1996

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ABSTRACT

Boiler chemical cleaning (BOCC) and high-pressure water lancing operations were performed during the Bruce A 1993 Unit 4, 1994 Unit 3, 1995 Unit 1 and 1996 Unit 3 outages to remove secondary-side deposits. High-pressure water lancing focused on three boiler areas: tube support plates (TSPs) to remove broached hole deposits, hot leg U-bend supports (HLUBS) to dislodge deposits contributing to boiler tube stress corrosion cracking (SCC) and tube sheets with the aim of removing accumulated sludge piles and post BOCC insoluble residues. The chemical cleaning processes applied were modified versions of the one developed by the Electric Power Research Institute/Steam Generator Owners Group (EPRI/SGOG). During these BOCC operations, corrosion for several key boiler materials was monitored and was well below the specified allowances.

Boiler chemical cleaning and tube sheet lancing removed about 6,250 and 2,200 kg of deposit respectively from Unit 4 boilers in 1993. The BOCC process involved an initial copper removal cycle, magnetite removal step, a final copper cycle and passivation step in that order. Tube sheet lancing operations, done after chemical cleaning, removed accumulated sludge from the cold leg and outer hot leg areas down to the tube sheet. However, hard tube deposits roughly 18 cm (7 inches) above the tube sheet were left in the hot leg central regions. High-pressure water lancing of the HLUBS, before or after BOCC, had limited success in cleaning the scallop bar surfaces of these U-Bend supports and left most hourglass (tube land) areas filled with deposit. In contrast, the combined effect of water lancing and BOCC left most TSP broached holes in an almost "as new" condition. Minor deposits remained in the TSP land areas.

The BOCC operations performed on Unit 3 in 1994 dissolved about 6,800 kg of deposits. For this BOCC campaign, the cleaning sequence was the same as applied in Unit 4, but the magnetite step was lengthened from 40 to 100 hours to enhance cleaning of the U-bend supports. The combination of pre and post BOCC lancing left HLUBS scallop bars cleaner than those in Unit 4, but did not remove the hourglass deposits. Tube sheet lancing before BOCC dislodged roughly 1,770 kg of sludge, compared with 875 kg of material after BOCC. Tube sheets were left in a similar condition to those in Unit 4 the year before; cold leg and outer hot leg areas were cleaned down to the tube sheet and hard tube deposits about 15 cm (6 inches) high remained in the hot leg central areas. As in Unit 4 a year earlier, water lancing and BOCC left TSP broached holes nearly deposit-free with minor deposits in the tube land regions.

To enhance cleaning of the HLUBS hourglasses and TSP land areas, the BOCC process was modified for Unit 1 in 1995; the low temperature magnetite step was shortened to about 24 hours and followed by a 67.5-hour EPRI/SGOG-type crevice cleaning step applied at 121°C. The latter step involved ~1-minute steam drum vents every hour to induce boiling and enhance crevice deposit dissolution. The sequence of pre and post BOCC lancing activities was the same as performed during the 1994 Unit 3 outage. In total, the Unit 1 BOCC process dissolved almost 8,500 kg of deposits. Post water lancing inspections of the HLUBS after BOCC showed that more scallop bar surface and hourglass deposit had been removed compared with the Unit 3 operations a year earlier. However, the hourglasses were only partially cleaned out. About 2,000 and 520 kg of tube sheet sludge was removed by water lancing before and after BOCC respectively. Tube sheets were left in virtually the same condition as those in Unit 4 and Unit 3 after BOCC and water lancing; hard tube scale about 18 cm (7 inches) above the tube sheet remained in the hot leg central regions. The combined cleaning operations left TSP broached holes nearly deposit free, but again, minor residues remained in the tube land areas.

In an effort to maximize deposit removal from the HLUBS hourglasses, a modified BOCC process was qualified for recleaning Unit 3 in 1996. The BOCC process performed involved a copper removal step, crevice clean and a proprietary copper/passivation step in that order. The crevice solvent was applied for 100 hours at 107°C while performing 2 vents per hour. Since the TSP broached holes were left nearly deposit free after the 1994 cleaning activities, pre and post BOCC lancing was limited only to the HLUBS and tube sheet areas. Post lancing visual inspections of the HLUBS after BOCC showed scallop bar surfaces and hourglasses to be almost free of deposits; only thin residues remained in the hourglass areas. The BOCC operations removed about 2,530 kg of deposit, while the pre and post BOCC tube sheet lancing activities dislodged approximately 162 and 46 kg of tube sheet sludge respectively. The height of the hard tube scale in hot leg central areas above the tube sheet, was reduced by 2.5-6 cm (1-4 inches) in most Unit 3 boilers by the BOCC process. Hard sludge piles about 8 cm (5 inches) high were evident in some of these hot leg regions. As expected, TSP broached holes appeared almost "as new" and minor residues remained in the land regions.

1.0 INTRODUCTION

1.1 Bruce A Steam Generator Features

The Ontario Hydro nuclear generating system currently consists of 20 pressurized heavy water (CANDU) reactors spread over three sites: the Pickering, Darlington and Bruce stations. The Bruce Nuclear Power Development, in Tiverton Ontario, is the location of eight reactors, with the Bruce A station housing Units 1 to 4. Bruce A Unit 2 started operations in January of 1977 and the remaining three units went on-line by 1979. In 1994, Ontario Hydro decided to lay up Unit 2 partly due to the poor condition of its boilers and to maintain the option of returning it to service if a future business case can justify refurbishment.

Each Bruce A unit contains eight recirculating boilers arranged in east and west banks. Boilers 1 to 4 and 5 to 8 make up the west and east banks respectively. A common steam drum connects the four boilers in each bank, a feature unique to the Bruce A station. For each bank of four boilers, there are 2 external preheaters. Figure 1 shows a cutaway view of a Bruce A boiler and steam drum. Table 1 summarizes key boiler features including tube and tube support materials.

2.0 Steam Generator Secondary-Side Deposits

During their operating lifetimes, Bruce A boilers accumulated significant quantities of secondary-side deposits that were introduced via the feed water. These impurities resulted from the corrosion of feed water system components and condenser leaks. The deposits typically contain 30-35% iron (mostly as Fe_3O_4), 35-45% copper (mostly as metallic Cu), 5-10% zinc (as ZnO), 1-5% nickel (as NiO) and minor amounts of other metallic oxides.

Beginning in the late 1980s, boiler water level oscillations became a recurring problem at Bruce A. In 1988, Boiler 3 in Unit 2 experienced water level oscillations which forced a Unit power derating to alleviate the problem. Over the next few months, Unit 2 was eventually derated to 72% full power operation to avoid the oscillations. Broached hole blockage in the upper tube support plates (TSPs) was suspected as the root cause of the problem and was confirmed later that year by fibrescopic visual inspections.¹

High-pressure water lancing equipment, developed and operated by Babcock and Wilcox Canada (BWC) Ltd., was used to clean the upper TSPs, enabling Unit 2 to return to full power operation. Around the same time, boilers in Unit 1 began to experience similar level oscillations which also forced a unit derating. As in Unit 2 earlier, Unit 1 returned to full power after cleaning the upper TSPs by high-pressure water lancing.² Although water lancing was recognized as an effective temporary solution, boiler chemical cleaning (BOCC) was developed as a more long-term measure.

A more serious problem associated with the build up of secondary-side deposits is stress corrosion cracking (SCC) of boiler tubes in the area of the hot leg U-bend supports (HLUBS), due to:

1. High local mechanical stresses due to support stack growth caused by the accumulation of deposits between scallop bars.
2. A boiler tube material (I-600) susceptible to SCC.
3. Accumulated surface and hourglass (tube land) deposits that promote a localized corrosive environment and scallop bar degradation.

In Unit 2, the SCC-related tube failures and scallop bar degradation were accelerated by lead contamination from a lead shielding blanket left inside a boiler during a unit outage. These tube failures along with overall boiler condition were major contributing factors in the decision to lay up the unit. Scallop bar decay was also discovered in varying degrees during pre and post cleaning inspections of the Units 1, 3 and 4 HLUBS and is described in greater detail in Section 5.0.

The build up of secondary-side deposits also led to concerns over the long-term integrity of boiler tubes above the tube sheets. The primary concern was the possibility of under deposit tube pitting and eventual tube failures in the tube sheet area where sludge piles had accumulated. Minor tube pitting has been found in this area, but more recently, circumferential tube cracking was identified in the tube sheet regions of several Unit 1 and Unit 4 boilers.

3.0 Boiler Cleaning Methods: Chemical Cleaning and Water Lancing

Soon after the Unit 2 boiler oscillation problems began in 1988, Bruce A recognized the need for a long-term solution. Chemical cleaning was chosen as the most viable approach, with the initial intent of applying the process on Unit 2 boilers only. However, later inspections revealed that heavy fouling on the secondary-side was common to boilers in all four units. As a result, the Bruce A station decided to chemically clean all boilers in Units 1 to 4 over a four-year period starting in 1993.

Pickering Unit 5 boilers were chemically cleaned in 1992 using a modified version of a process developed by the Electric Power Research Institute/Steam Generator Owners Group (EPRI/SGOG).³ This cleaning operation demonstrated that:

1. Deposits in fully blocked broached holes were not removed by chemical cleaning. However, partially blocked broached holes could effectively be cleaned out by the BOCC process.
2. The chemical cleaning solvents did not significantly penetrate hard and thick tube sheet sludge piles not removed by water lancing.
3. Tube scale and deposits on large surfaces were effectively removed.

After reviewing the Pickering Unit 5 BOCC operations, the Bruce A boiler cleaning strategy was subsequently revised to include high-pressure water lancing to help remove as much deposit as possible before BOCC. High-pressure water lancing operations focused on three boiler areas: HLUBS, TSPs and the tube sheets. At first, chemical cleaning was carried out with the aim of dissolving bulk secondary-side and broached hole deposits. Later, the importance of cleaning the U-bend areas became more evident. Combined chemical cleaning and lancing operations were carried out on Unit 4 in 1993, Unit 3 in 1994, Unit 1 in 1995 and again in Unit 3 in 1996. Section 4.0 describes the BOCC and lancing equipment used for these cleaning campaigns. The strategies, rationale for changes made for each cleaning operation and results are detailed in Section 5.0

4.0 Cleaning Processes and Equipment

4.1 Chemical Cleaning

To meet the 4-year schedule for cleaning boilers in all four Bruce A Units, the station issued tenders for the design, supply and operation of BOCC equipment and a corrosion monitoring system (CMS) in 1990. PN Services (then Pacific Nuclear and later VECTRA Technologies) and Babcock and Wilcox Nuclear Services (BWNS) (later Framatome Technologies Inc., FTI) received the contracts for the BOCC equipment and CMS respectively the following year.

The Bruce A station owns the BOCC and CMS equipment, but purchased operation/refurbishment services from the individual vendors for each clean. Table 2 summarizes several features of the BOCC equipment and CMS. Figure 2 depicts the lay out for the BOCC system components outside the Bruce A power house, while Figure 3 shows a flow diagram of the systems' boiler attachments and components inside the Power House. To minimize maintenance and lay-up requirements between cleans, the BOCC systems' wetted parts were constructed of stainless steel.

The contract for process qualification was awarded to BWNS, with the aim of removing an

estimated deposit loading of about 25,000 kg for all eight boilers in each Bruce A unit. This deposit estimate was based on:

1. Density measurements performed on deposit flake samples.
2. Tube deposit thickness measurements made from an inspection port aligned with the no-tube-lane.

The EPRI/SGOG cleaning method was chosen for qualification over the higher temperature cleaning processes, which use primary side heat, for several reasons:

1. The EPRI/SGOG process was well developed and had a large corrosion data base.
2. The high temperature processes were felt to be inadequate for removing high copper levels in secondary-side deposits.
3. High corrosion rates even at low copper levels were suspected at the higher temperatures.
4. There were concerns over delayed hydride cracking of pressure tubes and stresses resulting from steam drum temperature differentials, if a high temperature process employing primary side heat was used.

The EPRI/SGOG process uses separate solvents to remove copper and magnetite, cleaning crevices and passivation. Table 3 lists the solvents applied at Bruce A along with the application conditions. The qualification program was carried out to determine the sequence of cleaning steps best suited to dissolve Bruce A boiler deposits without exceeding preset corrosion limits for the following key materials (corrosion limits are shown in parenthesis):

- *AISI-1018 - U-bend supports (3.0 mils, later 6.0 mils for Unit 1 in 1995 and Unit 3 in 1996)
- *SA-515, Gr.70 - TSPs (3.0 mils, later 6.0 mils for Unit 1 in 1995 and Unit 3 in 1996)
- **Shielded Metal Arc Weld (SMAW) E7018 A1 - Welds(27.5 mils)
- **AISI-1015 - Internals (27.5 mils)

* Critical Materials

** Most Susceptible Materials

Corrosion limits for AISI-1018 and SA-515, Gr.70 were based on Flow Induced Vibration analysis of post BOCC scenarios and carried out by Ontario Hydro Technologies (OHT).

From the qualification tests, it was expected that the cleaning sequence for Unit 4 boilers in 1993 would be:

1. An initial copper cycle with multiple copper steps; the number of steps depended on the copper loading.
2. Low volume rinses followed by a full volume rinse.
3. A magnetite removal step (40 hours max.)
4. Low volume rinses followed by a full volume rinse.
5. Repeated copper and magnetite cycles, as well as low/full volume rinses as necessary.
6. Low volume rinses followed by a final full volume rinse and passivation.

4.2 Water Lancing

Babcock and Wilcox Canada (BWC) Ltd. received the contract to supply the high-pressure water lancing systems to clean the HLUBS and TSPs. The automated tube sheet lancing system was designed and built by Foster Miller Inc. (FMI) and is based on their Consolidated Edison Combined Inspection and Lancing (CECIL®) technology. Table 4 summarizes several key features of the HLUBS, TSP and tube sheet lancing systems.

Water lances used to clean the upper TSPs in Unit 1 and 2 boilers in 1989 and 1990 were originally designed, built and qualified by BWC to remove broached hole deposits in the upper TSPs. These thin, flexible intertube lances were constructed of stainless steel tubes encased in a

rigid plastic body (See Figure 4) and typically operated at a qualified nozzle pressure of 10,000 psig. Since the lances had limited flexibility, they could only be inserted into 30° tube lanes with the help of an adjustable guide, placed in the no-tube-lane through an external port, that allowed access through the boiler shell and shroud. At best, up to 65% of the TSP areas could be accessed by this method.^{1,2}

In 1992 and 1993, BWC supplied equipment for tube sheet cleaning operations performed on Pickering Unit 5 and 6 boilers. Water lances used for these cleans were modified versions of the ones used for the Bruce A Unit 1 and 2 operations and were designed to enter 90° as well as 30° tube lanes from the no-tube-lane. Two design improvements made this possible:

1. Replacing stainless steel tubing with Kevlar™ wrapped flexible tubing.
2. Substituting the rigid plastic around the tubing with a more pliant material.

These types of lances were used in cleaning the HLUBS and TSPs in Bruce A boilers by accessing 90° tube lanes through external lancing/inspection ports to provide the maximum coverage possible. By this method, roughly 83% of the total TSP area could be water lanced, compared with approximately 65% by accessing the 30° tube lanes only. The remaining 17% cannot be accessed due to tie rod interference in the NTL and within the tube bundle (Refer to Table 1). Up to 100% coverage of the HLUBS top or bottom sides is theoretically possible by lancing via the 90° tube lanes.

The key components of the tube sheet lancing system are described in Table 4. Figure 5 depicts several CECIL® components as they would appear within the boiler.

5.0 STEAM GENERATOR CLEANING RESULTS

Table 5 provides a summary of the chemical cleaning operations performed over 1993 to 1996, while Table 6 summarizes the corrosion data.⁴⁻⁷

Corrosion was measured on-line during BOCC using zero resistance ammetry (ZRA) and linear polarization techniques. On-line measurements were used for process surveillance and control. All final reported corrosion values were determined from coupons mounted inside the boilers during BOCC and removed afterwards.

Waste quantities for each clean are shown in Table 5. Except for the Unit 1 operations, the amount of waste produced in successive cleans was reduced. Additional waste was produced during the 1995 Unit 1 clean compared with the Unit 3 operation the year before because of the additional crevice cleaning step. The radiation levels in BOCC waste were always low (<2 µCi/kg gross β and γ radiation), allowing transfer to the site Spent Solvent Treatment Facility (SSTF) under Unconditional Transfer Permits. Two transfers of rinse water produced during the Unit 4 BOCC required Conditional Transfer Permits because of tritium contamination in the building steam used to heat the solvents and rinse water.

A brief summary of the pre and post BOCC water lancing operations is given in Table 7.⁸⁻¹⁸ Sections 5.1-5.4 further describe the BOCC and lancing operations and modifications made in successive cleaning campaigns. The 1994 Unit 1 TSP and 1995 Unit 4 HLUBS lancing activities are not discussed in detail but are briefly summarized in Table 7.

5.1 Unit 4 – 1993

Throughout 1992, several Unit 4 boilers experienced minor level oscillations relative to those seen in Units 1 and 2 during the late 1980s. The initial plan for the 1993 Unit 4 outage involved inspecting and, if necessary, water lancing TSPs 3-7 only. During this outage, the water lancing scope was expanded when a decision was made to develop and use equipment to clean the HLUBS top and bottom sides. This required installation of a special lancing/inspection port aligned with the gap between tube rows 14 and 15 (See Table 1). Due to outage scheduling

difficulties, the HLUBS lancing nozzles could only be installed on the west bank boilers after BOCC and on east bank boilers prior to BOCC. As a result, HLUBS in the west bank were only water lanced after BOCC, while those in the east bank were lanced before and after BOCC.

The scope of the lancing operations was further increased to include tube sheet cleaning when access to these areas became possible through the use of temporary bellows containment seals. However, these seals became available only after chemical cleaning. Once the seals were in place, access man ways could be cut into the boiler bellows without breaching containment, allowing the installation of TSP 1&2 and tube sheet lancing/inspection ports.

Boiler chemical cleaning operations were performed on the west bank, east bank and on the preheaters in that order. Section 5.1.1 describes the results of these BOCC operations, while Section 5.1.2 details the Unit 4 water lancing activities.

5.1.1 Chemical Cleaning

The BOCC operations removed 6,254 of deposits from the boilers, compared with 190 kg of material from the preheaters. Boiler tube surfaces and TSP broached holes were left with an "as new" appearance.¹⁹ Actual deposit removal was only about a quarter of the estimated 25,000 kg loading (See Section 4.1). The preheater clean, not summarized in Table 5, involved two copper steps followed by a magnetite step. Most of the material removed from the preheaters contained magnetite and corrosion for this cleaning operation was well within allowance.²⁰ In both the west and east bank boilers, only the initial copper step achieved a high loading, while the subsequent copper steps used up only a fraction of the solvent capacity.

From both on-line and actual coupon weight loss measurements, a corrosion gradient effect was noticeable during chemical cleaning; the highest corrosion occurred in the lower boiler regions near the tube sheet sludge piles. This behavior had not been observed during chemical cleans carried out elsewhere and a definitive explanation is not available. One possibility is this phenomenon may have occurred in cleans done in other stations, but was not observed because of the relatively fewer numbers of corrosion probes installed. Another conceivable reason is that high local deposit loadings near the tube sheet resulted in higher, local dissolution rates, causing more corrosion.

During the west bank clean, the magnetite step was stopped after about 8 hours since the magnetite dissolution had nearly plateaued and the indicated corrosion for the critical material (SA-515) approached its limit. Since this was the first BOCC campaign at Bruce A, it was not known how much corrosion would occur during the final copper and passivation steps. By terminating the magnetite step at that stage, it was felt there would be enough of the remaining corrosion allowance to permit carrying out the final two steps. In reality, corrosion during the final copper and passivation steps was low and overall corrosion remained well within allowance.

After reviewing the results from the west bank operations, the magnetite step for the east bank clean was extended to the full 40 hours. Subsequently, more magnetite was removed from the east bank boilers and, as described in Section 5.1.2, there was reduced blockage of broached holes in TSPs 1&2 after chemical cleaning.

Although the 1993 Unit 4 cleaning operations were successful, two major operational problems occurred. The first event occurred after the stainless steel hydrogen peroxide "day tank", containing about 5,000 L of 35% peroxide, became contaminated with copper solvent due to a passing check valve. Exothermic peroxide decomposition accelerated due to the catalytic effects of dissolved copper and, after about 5 hours, the contents of the tanks were violently released into the environment. Fortunately, the peroxide handling system was designed to handle such an event and equipment damage was minimal. The main impact from this incident was a several-day delay while a root cause investigation was carried out and procedures were modified to prevent a recurrence.

The second incident was the discovery of a white residue which coated the steam drum after the east bank operations. Analysis of this residue revealed it was a component of CCI-801 corrosion inhibitor. Nitrogen sparge rates during the east bank clean had been increased greatly and it was believed that magnetite solvent droplets containing inhibitor were entrained and deposited on the steam drum. Industrial hygiene concerns made work inside the steam drum much more difficult and time consuming due to additional protective equipment required. Sparge rates were greatly reduced during future cleans to minimize this problem.

5.1.2 Water Lancing

The strategy for cleaning the TSPs was to limit water lancing to those plates showing only >40% broached hole blockage. Where possible, 2 TSPs were simultaneously cleaned through a port situated at the mid span between them and aligned with the NTL. Lancing ports were installed between TSPs 6&7, 4&5 and later (post BOCC) for TSPs 1&2. The decision to install ports for TSP 3 depended on the pre lancing inspection results on one boiler in each bank. If required, the TSP 3 lancing/inspection ports was installed closer to this TSP because of interference from the blowdown header (See Figure 1).

Before chemical cleaning, water lancing reduced broached hole blockage from up to 100% to 0-10% (10-20% at worst) for TSPs 4 to 7 in the west bank, and TSPs 3 to 7 in the east bank. Post BOCC visual inspections of these same support plates showed these support plates to be virtually deposit free with 0-5% blockage. The post BOCC inspections of TSPs 1 and 2 in the east and west banks showed a marked difference. In the west bank, where a shorter magnetite step was performed, up to 100% broached hole blockage was still present in several areas. Water lancing of these regions reduced blockage to 20% or less. In contrast, broached holes in TSPs 1 & 2 in the east bank boilers, which underwent a 40-hour magnetite step, had only 0-5% blockage. Tube land deposits were evident in all TSPs after water lancing and chemical cleaning.

During the HLUBS water lancing activities, access to the HLUBS top and bottom sides varied from 65-95% due to misaligned tubes. This was caused by a combination of stack growth, broken forks and scallop bar deterioration.²¹ Lancing operations done in the east bank before BOCC removed enough surface deposit to expose some of the scallop bar surfaces but left the hourglass regions with residual deposit. The post BOCC operations left these same areas with less surface deposit but did not clean the hourglass areas (See Table 7). Except for Boiler 1, which showed 60-90% HLUBS surface exposure, the lancing operations in the west bank were unable to achieve the same surface cleanliness seen in the east bank.⁸ Two factors likely contributed to this difference:

1. West bank boiler HLUBS were not lanced before BOCC. As a result, deposits probably remained thick enough to prevent effective penetration and removal by BOCC solvents.
2. The magnetite step during the west bank clean lasted only about 8.5 hours, compared with 40 hours for the east bank.

Post BOCC tube sheet inspections of Boiler 7, before lancing, showed maximum sludge heights of roughly 36 and 31 cm (14 and 12 inches) in the center of the hot and cold leg sides respectively. Repeated passes with the 90° barrel spray unit cleaned the cold leg and outer hot leg areas down to the tube sheet. The remaining shadow deposits were removed with a side-shooting lance.

Hard, tenacious tube scale prevented lances from fully entering the hot leg central regions of Boiler 7, with access limited to about 18 cm (7 inches) above the tube sheet. Sludge piles were not evident and tube sheet assessments could not be done in this area due to the fibscopes' limited visual range. This finding was consistent for all Unit 4 boilers. The hard tube scale in the hot leg regions remained intact despite repeated attempts at removal with either the straight-ahead lance or lances fitted with offset nozzles.

On average, the CECIL® tube sheet lancing system removed about 275 kg of wet sludge per boiler.^{8,11} The percentage of chemical cleaning insolubles could not be determined since all tube sheet lancing operations were performed post BOCC.

5.2 Unit 3 - 1994

After reviewing the 1993 Unit 4 experiences, several changes were made to the water lancing and BOCC procedures:

1. The magnetite step was qualified for and extended to 100 hours to enhance cleaning of the U-bend supports.
2. Unit 3 preheaters were not chemically cleaned. This decision was based on the previous efforts required to remove the relatively small quantity of deposit from the preheaters in Unit 4.
3. TSP lancing was limited only to areas with >60% broached hole blockage before BOCC, compared with the >40% blockage criterion used during the 1993 Unit 4 operations. It was expected that the longer magnetite step applied in Unit 3 would enhance deposit removal from broached holes.
4. Tube sheets were water lanced before and after chemical cleaning to allow access to the hard tube deposits by the chemical cleaning solvents.
5. All boiler HLUBS were lanced before and after BOCC to maximize deposit removal from the scallop bar surfaces and hourglass regions. An automated HLUBS lancing system was developed by BWC for this purpose and to reduce dose uptake inside the boiler room.

Sections 5.2.1 and 5.2.2 describe the impacts of these modifications.

5.2.1 Chemical Cleaning

The chemical cleaning operations removed about 6,800 kg of deposit from Unit 3 boilers (See Table 5). Visual inspections done after BOCC showed tube surfaces and TSP broached holes to be virtually free of deposit. In addition, inspections of the HLUBS were carried out immediately after BOCC from inside the steam drum. It was apparent from these inspections that the HLUBS surfaces were much cleaner than those in Unit 4 a year earlier, but deposits remained in most hourglass areas. The improvement in overall cleaning effectiveness was mainly due to the longer magnetite step. In addition, there was no inhibitor deposits found in the steam drum after BOCC.

Corrosion was within the allowances for all key boiler materials. As in Unit 4 a year earlier, corrosion rates were higher in the lower boiler regions, but less in magnitude. This was likely the result of removing loose tube sheet deposit before BOCC. Examination of the SMAW corrosion coupons, which were located close to the tube sheet during BOCC, showed severe localized "worm-hole" like corrosion up to 750 µm (30 mils) deep. Visual examinations done on actual boiler SMAW welds located close to the coupons revealed minimal corrosion. One possible explanation for this discrepancy was that the coupons were partially buried in loose tube sheet deposits, or that some other localized conditions caused the observed localized pitting of the coupons. The SMAW corrosion reported in Table 6 was determined from the weight loss measurements made on pitted coupons.

5.2.2 Water Lancing

Boiler TSP inspection/lancing nozzles were installed in the same locations as in Unit 4. Pre water lancing visual inspections revealed TSPs in Unit 3 boilers to be much cleaner than found in Unit 4 the year before. Only TSPs 1, 2 & 7 in a few Unit 3 boilers had >60% broached hole blockage and were water lanced to reduce blockage to 10-20% or less. Post chemical clean inspections of TSPs that were either lanced or had <60% blockage and did not require lancing, revealed blockages has been reduced to 0-5% (10-20% in the worst case). Deposits were found in most TSP land areas examined.¹⁰

Water lancing of the HLUBS before BOCC removed enough deposit to expose part of the

scallop bar surfaces including a few scallop divisions, but did not clean hourglass regions. Access to the target 90° lanes ranged from about 63 to 99% of the available tube lanes before BOCC due to restrictions. However, average access after BOCC increased to about 98% due to the removal of tube deposits by the BOCC process.

As mention in Section 5.2.1, a general inspection done inside the steam drum just after chemical cleaning, but before water lancing, revealed the Unit 3 boiler HLUBS to be much cleaner than those in Unit 4 after the 1993 chemical clean. This was attributed to the longer magnetite step performed in Unit 3. Visual inspections of selected tube lanes after chemical cleaning, but before water lancing, showed clean tube surfaces except for the areas just above the scallop bars where dark deposits covered most hourglasses and scallop bar surfaces.

Post lancing visual inspections after BOCC revealed:

1. Roughly 50% surface exposure on the top sides, compared with 80% surface visibility on the bottom. As expected, the scallop bars appeared much cleaner than after the pre chemical clean lancing operations.
2. A light, red surface oxide coating on most scallop bar surfaces on both sides. This oxide likely formed after water lancing.
3. Small tube collars that filled most hourglasses and extended a few millimeters above the scallop bar surfaces.
4. No sign of scallop bar degradation as seen in Unit 4 the previous year. This was not surprising since the Unit 3 HLUBS stack growths were far less than those for measured for Unit 4 in 1993.²²

Before chemical cleaning, pre lancing tube sheet inspections of Boiler 5 showed maximum sludge heights of roughly 23-25 cm (9-10 inches) on the hot and cold leg sides. The combination of the 90° and 30°/150° barrel sprays effectively cleaned the cold leg and outer hot leg areas down to the tube sheet, with thin deposits left in the original location of the pile. Hard tube deposits, similar to those left in Unit 4, were found in the hot leg central area; this limited lance insertion to no more than 8-15 cm (3-6 inches) above the tube sheet and prevented tube sheet visual inspections in this area. Hard sludge piles were not evident in the restricted hot leg area.

The post lancing tube sheet condition of the remaining Unit 3 boilers closely resembled that of Boiler 5. Although hard tube scale was also found about 2.5-5 cm (1-2 inches) above the tube sheet in some cold leg areas, the tube sheet was clearly visible in these regions. The pre chemical cleaning water lancing operations removed about 222 kg of wet sludge per boiler.

Tube sheet lancing operations after BOCC dislodged about 109 kg of residue per boiler. Although the cold leg and outer hot leg areas were cleaned down to the tube sheet, hard tube deposits about 8-15 cm (3-6 inches) above the tube sheet remained in the hot leg central areas. The persistence of hard tube collars most likely resulted from a rapid build up of insoluble BOCC residues around the tubes and on top of the tube sheets, possibly during the initial copper step. Once the insolubles settled on the tube sheet, they became an effective barrier between the chemical cleaning solvents and the hard deposits.

5.3 Unit 1 - 1995

Deterioration of the U-bend support structures in all Bruce A Units, along with the inability of the low temperature EPRI/SGOG BOCC solvents to remove the U-bend deposits in Units 3 and 4, raised concerns over the effect on the remaining boiler life. The focus of BOCC operations at Bruce A consequently changed from bulk deposit removal and broached hole cleaning to removing deposits from the U-bend supports. It was recognized that a more aggressive process was required and a new cleaning sequence incorporating an EPRI/SGOG crevice clean at 121°C was qualified.

A crevice cleaning process involves heating the solvent above its normal boiling point with

periodic depressurizing to induce boiling in the upper solvent region. Deposit dissolution is enhanced over the conventional magnetite removal step by the higher application temperature and turbulence caused by boiling. The periodic boiling cycles are believed to force fresh solvent into crevices thereby allowing deposit dissolution to continue. Under non-boiling conditions, the solvent inside the crevices rapidly becomes spent and deposit dissolution ceases. Without an active mechanism to replenish solvent within crevices, deposits in these regions remain intact.

The chemical cleaning application sequence qualified for the Bruce A Unit 1 was similar to the one applied on Unit 3 in 1994 except:

1. The magnetite step was shortened to 24 hours. Data from the previous Unit 4 and Unit 3 cleans showed that iron loading in the magnetite solvent plateaued after about 10 hours.
2. A boiling crevice cleaning step followed the magnetite step. A standard EPRI/SGOG crevice cleaning process (See Table 3) was selected for Bruce A since the 120-125°C application temperature could be achieved with the BOCC equipment then available. Vents were planned for about 1 minute each hour and performed by opening steam drum relief valves that discharged directly to the atmosphere through a stack located on the station roof.²³

Due to concerns over SMAW corrosion, the CCI-801 inhibitor concentration in the magnetite solvent was increased from 1 to 2.5%. The specification for inhibitor concentration in the crevice solvent was set at 3% owing to similar concerns.

Solvent and process qualification testing for the Unit 1 clean showed that AISI-1018 U-bend scallop bar material and, to a lesser extent, SA-515 Gr.70 TSP material were susceptible to high aspect ratio pitting in the crevice solvent. One possible explanation was that the crevice solvent attacked the manganese sulfide "stringers" created during the rolling process of AISI-1018 carbon steel. Maximum exposure duration for AISI-1018 was found to be 50 hours, compared with 75 hours for SA-515 and other boiler materials. Pitting was found to be excessive beyond these times and the total process time was therefore limited to 67.5 hours. The solvent level was maintained above the top of the U-bend for a maximum permissible exposure of 50 hours. Afterwards, the level was lowered below TSP 5 to allow cleaning of the lower boiler regions including the tube sheet for the remaining 17.5 hours, without further impact on the U-bend supports.

During field application, AISI-1018 and SA-515 Gr. 70 coupons were removed on-line and subjected to metallographic examination for pitting. On-line coupon removals started at 25 hours and were repeated at 35 and 45 hours into the crevice cleaning step.

Before the Unit 1 clean, corrosion allowances for the critical U-bend support and TSP materials were reevaluated. Based on FIV analyses, the corrosion allowances for these materials were raised from 75 µm (3.0 mils) to 150 µm (6.0 mils).²⁴

Water lancing operations carried out during the 1995 Unit 1 outage closely paralleled those performed in Unit 3 the year before. However, the upper TSPs in Unit 1 were water lanced late in 1994 to provide temporary relief for level oscillations until a full scale lancing and BOCC campaign was executed in 1995 (See Table 7). The 1995 TSP lancing activities before BOCC were restricted to TSPs with >60% broached hole blockage, but carried out with a newly developed automated system to reduce dose uptake inside the boiler rooms (See Table 4). As in Unit 3, tube sheets and HLUBS were lanced before and after chemical cleaning.

5.3.1 Chemical Cleaning

The Unit 1 BOCC operations removed about 8,500 kg of deposit, compared with roughly 6,250 and 6,800 kg of material dissolved by the 1993 Unit 4 and 1994 Unit 3 cleans respectively. Corrosion of all materials monitored was well within their allowances, as shown in Table 6.

Forty-nine and 51 vents were performed during the crevice cleaning steps for the west

and east banks respectively. Each vent lasted about 1½ - 2 minutes and resulted in boiling depths of around 14 feet. The recovery time between vents ranged from roughly 30 to 90 minutes, with an average time of approximately 75 minutes. Most of this time was spent reheating the crevice solvent to 121°C by direct steam injection. Since the steam was at relatively low temperature, larger volumes of steam were required to reheat between vents relative to the steam lost during venting resulting in solvent dilution.

Metallographic evaluations of AISI-1018 U-bend coupons removed from boilers during the crevice step showed the onset of pits toward the end of the 50-hour duration at full height. The crevice solvent level was then dropped to below TSP 5 for the remaining 17.5 hours according to plan.

After BOCC, visual inspections of the HLUBS were performed and revealed that the HLUBS in Unit 1 were cleaned better than those in either Unit 3 or 4. In some cases, tube deposits present before BOCC were removed and the hourglass edges were clearly visible. However, these land regions were not completely cleaned out. Section 5.3.2 to follow describes the HLUBS condition assessments in further detail, along with TSP and tube sheet visual inspections

Although the Unit 1 clean was successfully executed, several operational problems occurred. During the initial 121°C hot rinse preceding the crevice step in each bank, the temperature differential between the top and bottom of the steam drum exceeded the permissible limit. Subsequent temperature data analysis from both events revealed that allowable stresses were not exceeded and the procedures for subsequent cleans were revised to avoid a recurrence.

During the west bank clean, a copper solvent spill occurred inside the Power House. The nitrogen gas supply was lost when high winds toppled over liquid nitrogen evaporators which were situated behind Unit 1 outside the station. Once the nitrogen pressure dropped to zero, copper solvent flowed back into the nitrogen sparging system pulse tank. A brass fitting at the bottom of the tank, which normally contained dry nitrogen, corroded and opened a spill path. The spill was quickly contained and the BOCC system was isolated from the leak point, allowing the copper step to continue without further incident. Brass fittings were replaced with stainless steel ones before the east bank operations.

5.3.2 Water Lancing

As in Units 3 and 4 previously, the combined effect of chemical cleaning and water lancing left TSP broached holes virtually deposit free. The amount of land deposits in the TSPs after BOCC appeared to be significantly less than in observed in Units 3 or 4 during visual inspections. This can be attributed to the addition of the crevice cleaning step in the BOCC process.¹³

Pre chemical cleaning lancing operations left about 50-80% of the HLUBS surfaces exposed on the top and bottom sides, but did not remove any hourglass deposits. In contrast, inspections done after chemical cleaning and water lancing showed 80-90% surface exposure and partial penetration into the hourglass deposits.

Further HLUBS condition assessments for each Unit 1 boiler after BOCC showed scallop bar degradation in varying degrees. This degradation followed the same trend found in Unit 4 a few months earlier; decay was found primarily in the HLUBS central regions, with the most severe degradation apparent in the hourglass areas (See Table 7). In contrast, the outer HLUBS areas appeared to be intact.^{13,14}

Before chemical cleaning, about 2,000 kg of loose sludge was removed from the tube sheets through a combination of 90° and 30°/150° low-pressure barrel sprays. Hard tube scale, about 23-37 cm (9-15 inches) above the tube sheet, prevented lance insertion into the hot leg central regions and tube sheet assessments in these areas. Roughly 2.5-7.5 cm (1-3 inches) of tube scale was also found in a few cold leg areas examined.¹⁵

The post chemical clean tube sheet lancing activities dislodged roughly 520 kg of BOCC insoluble residues. Inspections done afterwards showed that the height of the tube scale was reduced to a maximum of about 15 cm (6 inches) in six boilers. Roughly 2.5-5 cm (1-2 inches) of tube deposit remained in a few cold leg areas inspected. It is believed that the reduction in hard tube scale, not observed in Unit 3 a year before, resulted from:

1. Addition of the boiling crevice step to the BOCC sequence, and
2. The more effective tube sheet rinses after each cleaning cycle. These more vigorous rinses flushed out more of the undissolved particulates which settled on the tube sheet and sludge piles, and provided an effective barrier between the hard tube deposits and the cleaning solvents. Post BOCC tube sheet flushes in Unit 3 removed roughly 450 kg more of deposit compared with the same operations carried out in Unit 1.

5.4 Unit 3 - 1996

By 1996, Unit 2 had been laid up partly due to the poor condition of its boilers. Because of heightened concerns over degradation caused by crevice corrosion in the U-bend area, a case to perform crevice cleaning on Unit 3 and 4 boilers was submitted and approved in 1995.

Although the 1995 Unit 1 BOCC campaign resulted in significantly cleaner scallop bars and hourglass regions, further improvements in the cleaning process were clearly required to ensure the recleaning of Units 3 and 4 could be justified. To this end, the various parameters affecting the crevice solvents' potency were reviewed and a process qualification/optimization program for Units 3 and 4 undertaken. The susceptibility of AISI-1018 scallop bar material to pitting in the crevice solvent continued to be a major concern throughout the new qualification program and was closely monitored.

The test program focused on varying application parameters for the crevice solvent, but not for the copper solvent which was considered relatively benign. The three crevice solvent application scenarios were:

1. The same crevice solvent composition and application temperature, 121°C, as used in Unit 1 but with 2 vents per hour instead of 1. This test clearly showed the benefits of more frequent venting cycles. As a result, the crevice solvent was qualified for application for the same exposure duration as used during the previous Unit 1 clean: 67.5 hours total, with 50 hours at full height.
2. The same solvent and venting frequency as above, but applied at 107°C. It was hoped that the lower temperature would permit a longer exposure to the crevice solvent and more venting cycles before the onset of pitting in AISI-1018. This was found to be the case and the crevice solvent was qualified for application at 107°C with 2 vents per hour for up to 110 hours (maximum field duration = 100 hours).
3. The Babcock and Wilcox (B&W)/FTI high temperature process applied at 143°C. This process was successfully applied at several US utilities using primary heat to maintain the solvent temperature. During the Bruce A qualification tests, the high temperature process effectively cleaned experimental crevices but corrosion of AISI-1018 was unacceptably high. As a result, this high temperature process was not qualified for use at Bruce A. It was also unclear whether the BOCC equipment had the capabilities of reaching and maintaining the required process temperature in the permitted duration of the high temperature step.

A 3-step process was ultimately selected for use in Units 3 and 4. The cleaning sequence included a single copper step, followed by the 107°C crevice step with 2 vents per hour for 100 hours at full height, and finally, the B&W/FTI low temperature passivation step. Bruce A licensed the latter process from B&W/FTI.²⁵ Units 3 and 4 had been previously cleaned and the copper bearing components in the feed trains replaced. None-the-less, it was expected that there would be residual copper in the remaining tube sheet deposits. This necessitated an initial copper step to avoid excessive copper plate out and corrosion during the crevice step. In addition, the

B&W/FTI passivation process was selected to reduce outage critical path time and BOCC solvent waste. As in Unit 1 the year before, AISI-1018 and SA-515 Gr. 70 coupons were periodically examined during the crevice step to watch for the onset of pitting.

Free EDTA concentration was also identified as an important factor in the crevice solvents' effectiveness. During the Unit 1 clean, the use of direct steam injection heaters resulted in solvent dilution and free EDTA concentrations less than 100 g/L. For Units 3 and 4, a minimum free EDTA concentration of 170 g/L was specified. To avoid solvent dilution, a plate-type heat exchanger, heated by building steam, was installed in the BOCC system. Use of the new heat exchanger required removal of large condensate volumes due to the low quality building steam utilized for supplying heat.

Water lancing operations, before and after chemical cleaning, were limited only to the HLUBS and tube sheets. Lancing of the TSPs was not carried out since the supports were left virtually deposit free in 1994 and, by that time, BOCC was a proven method for cleaning partially blocked broached holes.

5.4.1 Chemical Cleaning

About 2,500 kg of deposits, primarily magnetite, were dissolved during the recleaning of Unit 3, compared with approximately 6,800 kg in 1994. The total corrosion measurements from both cleans were within the permitted allowances (Refer to Table 6).

For the east bank clean, the crevice step was executed as planned, i.e., at full height for 100 hours at 107°C and two 1-minute vents per hour. Visual inspections done after chemical cleaning showed broached holes and HLUBS scallop bar surfaces to be almost free of deposit. Nearly all hourglass areas examined were cleaned out and only thin residues were left behind in these land regions. From these inspections, it was evident that the crevice step applied in Unit 3 was much more effective than the one carried out in Unit 1 a year earlier. However, most tube sheet deposits remained intact, as described later in Section 5.4.2.

The crevice step for the west bank clean was modified in an attempt to enhance tube scale removal at the tube sheet. After 100 hours at 107°C and full height, the crevice solvent level was lowered to below TSP 2 and the temperature raised to 121°C. The 121°C phase of the crevice step lasted only about 5 hours because of free EDTA depletion and schedule constraints. As described Section 5.4.2 below, this process modification did not result in better tube scale removal in the hot leg area. Results from the post BOCC visual inspections of the west bank HLUBS were nearly identical to those of the east bank; hourglasses and scallop bar surfaces were nearly deposit free.

Operational difficulties during the second Unit 3 clean included a steam drum temperature differential event during the heat up rinse prior to applying the crevice step on the first (east) bank. Procedures were again revised prior to cleaning the second bank to avoid a recurrence.

A second upset occurred during the first vent cycle in the east bank crevice step. A small quantity of crevice solvent was ejected out of the safety relief when it was opened. This was unexpected since there was no similar occurrence during the 1995 Unit 1 clean, which involved a 121°C crevice step. The most likely explanation is that the crevice solvent tends to produce a stable foam at the lower application temperature of 107°C. To avoid this problem, the vent duration was reduced, which resulted in less vigorous boiling. In addition, the lower solvent injection nozzle was used to reduce nitrogen entrapment at the solvent surface.

A comment is warranted about the post BOCC start up chemistry. After the Unit 3 restart, boiler sulphate levels remained at elevated levels for an extended period. Increased blowdown kept the sulphate level within specification, but only at the expense of high demineralized water usage and lower Unit power output. It appears likely that the crevice solvent containing a sulfur-

bearing corrosion inhibitor was left behind in numerous cut boiler tubes and other steam drum and boiler dead legs. The inhibitor sulfur is rapidly converted to sulphate at operating temperatures, but diffusion back into the boiler water during operation could have caused the chronically high sulphate levels experienced. Another contributing factor was that virtually all boiler deposits in which the sulphate could previously hide out were removed from the Unit 3 boilers.

5.4.2 Water Lancing

Post BOCC inspections of the TSPs could only be performed in a few selected boilers due to schedule constraints. The inspections showed TSP broached holes to be virtually deposit free, as expected, with thin residues remaining in the land areas.¹⁶

Pre BOCC visual inspections done before lancing showed the HLUBS to be lightly coated with black deposits with many scallop divisions clearly visible. All hourglass areas were filled with deposits. The lancing operations carried out before BOCC cleaned the HLUBS top and bottom sides well enough to expose 70-100% of the scallop bar surfaces, but did not change the condition of the hourglass areas. At the end of the BOCC and lancing operations, 95-100% of the scallop bar surfaces were visible on both sides and nearly all hourglass land areas inspected were essentially free of deposits.

Tube sheet lancing operations before BOCC dislodged roughly 162 kg of sludge for all eight Unit 3 boilers, compared with 46 kg after BOCC (Refer to Table 7). Tube deposit profile maps generated before chemical cleaning and after water lancing were nearly identical to those produced at the end of the 1994 cleaning operations. The cold leg and outer hot leg areas were cleaned down to the tube sheet, but hard tube deposits remained about 13-15 cm (5-6 inches) above the tube sheet in the hot leg central areas preventing tube sheet inspections in these areas.¹⁸ However, several differences were observed during inspections after BOCC and lancing:

1. The height of the hot leg tube scale in seven boilers had been reduced by 2.5-10 cm (1-4 inches). There were no discernible differences between the east and west bank boilers.
2. Roughly 7.5-15 cm (3-6 inches) of hard sludge was evident in some hot leg areas which were previously inaccessible before BOCC.
3. The minor tube scale seen in a few cold leg areas before BOCC was removed.

Considering these findings, it is unlikely that the modified crevice step performed on west bank boilers enhanced tube scale removal in the tube sheet areas. The overall improvement in tube scale removal likely resulted from fewer insoluble residues being generated during the 1996 BOCC, thereby leaving more of the hard tube deposits exposed to the chemical cleaning solvents.

6.0 Review of BOCC and Water Lancing Operations

Plans to reclean Unit 4 boilers in 1998 were well advanced when the decision to shut down the Bruce A Units by March 31, 1998, was announced in August of this year. All four Units will remain shutdown until at least 2003. To restart, the Bruce A Units may require new boilers and pressure tubes. As a result, the Unit 4 BOCC operations were recently canceled.

None-the-less, it is important to mention the successes and lessons learned from BOCC and lancing operations carried out at Bruce A from 1993 to 1996. One of the most notable successes of these cleaning campaigns was the removal of about 30,700 kg of boiler secondary-side deposits from the three units over this period by the combination of water lancing and chemical cleaning. Several other noteworthy experiences gained from these cleaning operations are:

1. The combination of water lancing and chemical cleaning effectively rendered TSP broached holes deposit free. As a result, boilers in all three Bruce A units are expected to run until the scheduled shutdown without concerns over level oscillations.
2. The most effective crevice cleaning step to date was applied on Unit 3 boilers in 1996. As a

result. HLUBS degradation rates are expected to be significantly reduced for this Unit over its remaining life.

3. The tube sheet lancing system efficiently removed large quantities of loose sludge. However, improvements to the system are required to breakup hard sludge deposits.

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TABLE 1 BRUCE A STEAM GENERATOR DATA

Steam Generator Type:	Babcock and Wilcox inverted U design.
No. of Tubes/Boiler:	4,200
Boiler Tube Material:	I-600
Hot Leg Temperature:	304°C (579°F)
Cold Leg Temperature:	265°C (509°F)
No. of Tube Support Plates (TSPs)/Boiler:	Seven 2.54 cm (1-inch) thick TSPs spaced about 89 cm (35 inches) apart.
TSP Material:	SA-515, Gr. 70 carbon steel.
TSP Design features:	• Trefoil broached holes. • ~0.47 cm (0.18 inch) wide tube lanes at 90°, 30° and 150° to the no-tube-lane (NTL). • 4 tie rods located in NTL between TSP 1&7. Additional 20 tie rods located within the tube bundle.
No of U-bend Supports/Boiler:	3 sets of stacked scallop bars: one at 90° and the others on the hot and cold leg sides at 40° to the horizontal.
U-bend Material:	AISI-1018 carbon steel.
U-bend Support Design Features:	• Individual bars have half-tube scallops alternated from top to bottom. • Hourglass shaped land areas around each tube. • Supports held together at edges by studs and through the middle by forks (6 forks per support). • 90° support holds tube rows 15 to 95. * • Both 40° supports hold tube rows 42 to 95.*
No-Tube-Lane:	• Separates hot and cold leg sides. • ~6.85 cm (2.7 inches) wide. • 4 tie rods along the center.
Tube Sheet:	• 2.52 m (99 inches) in diameter. • 36.8 cm (14.5 inches) thick in the tube region. • Weld overlaid with I-82 on the primary side to facilitate tube welding.
Weld Material:	Shielded Metal Arc Weld (SMAW) E7018, A1

* Small gap present between tube rows 14 and 15 in the U-bend region. Rows 1-14 are unsupported.

TABLE 2 BOCC AND CMS SYSTEM DESIGN FEATURES

System	Feature	Description
BOCC	Location	- Process modules located and tanks outside on the North side of the Bruce A Power House (See Figure 2). - Process skids located inside the power house.
	Designers/Registration	- Designed by AECL and PN Services - Registered as a Class 6 non-nuclear system.
	Cleaning Capacity	System can clean 4 steam generators at a time.
	Process Control	- Manually operated system. - Critical valves & pumps can be controlled with computer located in Control Module. - Computer controlled by "In Touch" software and contains preprogrammed shutdown criteria for safe operation.
	Chemical Handling	35% or 50% (wt/wt) H_2O_2 and 99% EDA stored in rented road tankers fitted with temporary containment dikes. 40% (wt/wt) EDTA stored in one of four frac tanks. - CCI-801 inhibitor and 35% (wt/wt) hydrazine delivered in 350-550 gallon steel totes and off-loaded in the drum module. 30% (wt/wt) ammonium hydroxide delivered in 45 imp. gallon drums and off-loaded in drum module or from rental tanker (Unit 3, 1996). - Air powered diaphragm pumps used to transfer chemicals from the drum module to mix tanks.
	Solvent Preparation & Recirculation	- Copper, iron and rinse solvents prepared in 3 separate 136,000 liter tanks. - Recirculation pump can be valved to other solvent preparation systems if a pump failure occurs. - Up to 110,000 liters needed to fill 4 boilers and BOCC system lines. - Solvent can be recirculated up to 80 liters/second, i.e., ~1 system volume every 30 minutes. - Solvent introduced at top of boilers via 3" nozzle above U-bend area. - Solvent drained out through boiler blow down lines. ~100 kPa(g) nitrogen blank maintained inside boilers and steam drum to ensure adequate NPSH. - Constant nitrogen purge through steam drum to avoid hydrogen build up from carbon steel corrosion.
	Heating	- Initially through a combination of electric heaters and plant steam (~600 kPa(g)). - Plate-type heat exchanger installed prior to 1996 Unit 3 clean to achieve quick heat up and avoid solvent dilution by steam injection.
	Level Measurement	- Pressure difference between cover gas and nitrogen bubbles introduced into blow down box header is translated to level readings. - Static levels confirmed by sight glasses.
	Waste Handling	- Two main tanks enclosed in a containment dike receive waste. (Total capacity = 650,000 liters). 3 of 4 frac tanks act as backup for waste transfer. "Non active" waste must have <2μCi/kg total β & γ radiation. Spent Solvent Treatment Facility (SSTF) on site can only hold a limited quantity of active material. - Active waste can be transferred to contingency waste facility inside the station fence.

TABLE 2 (Continued)

System	Feature	Description
Corrosion Monitoring (CMS)	On-line measurement	• Combination of Linear Polarization (LP) and Zero Resistance Ammetry (ZRA) methods to measure general and galvanic corrosion respectively on-line. • Weight loss measurements for coupons and dimensional changes on mockups provide the official corrosion results.
	Locations	• LP, ZRA and coupons located at various boiler elevations to track and measure differences in corrosion.

TABLE 3 EPRI/SGOG CHEMICAL CLEANING SOLVENT COMPOSITION AND APPLICATION CONDITIONS

Solvent	Composition	Application Conditions
Copper	• 5% EDTA • EDA** to pH 10.0¹ • 3% hydrogen peroxide	• 25-35°C • ~8 hours
Iron	• 15% EDTA • 1% Hydrazine • Ammonium hydroxide to pH 7.0 • 1% CCI-801 corrosion inhibitor²	• 90-96°C • ~40 hours
Rinse/Passivation	• Ammonium hydroxide to pH 10.0 • 20-200 ppm hydrazine • EDTA <50 ppm • Fe <100 ppm • Cu <50 ppm	• 90-93°C (passivation) • ~8 hours
Crevice	• 20% EDTA • Ammonium hydroxide to pH 6.0 • 3.0% CCI-801 inhibitor	• 107-125°C³ • 50-100 hours • 1-2 vent per hour.

* EDTA = Ethylenediamine tetraacetic acid

** EDA = Ethylenediamine

¹ For Unit 3 in 1996, 30% ammonium hydroxide was used for pH adjustment.

² CCI-801 concentration increased to 2.5% for Unit 1 clean in 1995.

³ Unit 1: 121°C, ~ 1 vent per hour, full height for up to 50 hours & below TSP 5 for 17.5 hours.

³ Unit 3: 107°C, 2 vents per hour, full height for up to 110 hours.
(1996)

TABLE 4 WATER LANCING SYSTEM FEATURES

Lancing System (Designer)	Type	Key Features
TSP (BWC)	Semi-manual	• Used for 1993 Unit 4, 1994 Unit 3 and 1994 Unit 1 TSP cleaning operations. • Flexible intertube lances with the following typical dimensions: 294.6 cm X 0.29 cm X 3.81 cm (116 in. X 0.115 in. X 1.50 in) • Lances contain 6-8 flexible Kevlar™ wrapped tubes. • Water jets from lance directed parallel to boiler tubes. • 90° tube lanes accessed through a manually operated lance guide inserted in a port aligned with the NTL. • Lance movement controlled with an air drive. • Water supplied by high-pressure pump located outside the boiler room. • Water removed from boilers with a suction pump hooked up to 1-inch boiler blow down line and filters.
	Automated	• Used for Unit 1 operations in 1995. • Lances, lance guides and water supply/removal systems similar to those in semi-manual system. • 90° tube lanes accessed through port aligned with NTL. • Lance/guide drive assembly controlled by computer outside boiler room and has separate lance and guide drives. • System designed for remote operation of high-pressure pumps.
HLUBS (BWC)	Semi-Manual	• Used during 1993 Unit 4 U-bend lancing campaign. • Designed to enter gap between tube rows 14&15 through a port above TSP 7. • Lances, lance guides and pump/filtration assembly similar to semi-manual TSP system. • Lance guides built to rotate allowing access to the HLUBS top and bottom sides through 90° tube lanes. • Movement of lance controlled with an air drive.
	Automated	• Used during 1994 Unit 3, 1995 Unit 4, 1995 Unit 1 and 1996 Unit 3 cleaning operations. • Access to 90° tube lanes through gap between rows 14&15. • Lances, lance/guide drive assemblies and control similar to that of the automated TSP lancing system.
Tube Sheet (FMI)	Automated	• Used during 1993 Unit 4, 1994 Unit 3, 1995 Unit 1 and 1996 Unit 3 lancing campaigns. • Separate skids contain surge tank, filter housings, water storage tank, lance and barrel spray supply pumps. • High-pressure lance, for hard sludge removal, made of segmented metal pieces and fitted with 4 Kevlar™ pressure tubes and a fibrescope. • Access to 90° tube lanes through a port aligned with NTL. • 90° and 30°/150° barrel spray units used for low pressure tube sheet flushing operations. • Lances and barrel spray units were remotely controlled from a computer outside the boiler room.

TABLE 5 SUMMARY OF CHEMICAL CLEANING CAMPAIGNS

Unit 4 (1993)	Step No.	Step	Application Temperature (°C)	Duration (hours)	Deposit Removed (kg)	Total Waste Volume (liters)
Unit 4 (1993)	1	Cu1-1**	<35	~5	2,303	~1,744,000
	2	Cu1-2	"	~5	627	
	3	Cu1-3	"	~5	250	
	4	Fe1-1	~93	8.5 - west bank 40 - east bank	2,841	
	5	Cu2-1	<35	~8	233	
	TOTAL				6,254	
Unit 3 (1994)	Step No.	Step	Application Temperature (°C)	Duration (hours)	Deposit Removed (kg)	Total Waste Volume (liters)
	1	Cu1-1	<35	<5	2,359	~990,000
	2	Cu1-2	"	~8	412	
	3	Fe1-1	~93	100	3,859	
	4	Cu2-1	<35	~8	175	
	TOTAL				6,809	
Unit 1 (1995)	Step No.	Step	Application Temperature (°C)	Duration (hours)	Deposit Removed (kg)	Total Waste Volume (liters)
	1	Cu1-1	<35	<10	2,563	~1,108,000
	2	Cu1-2	"	<10	506	
	3	Fe1-1	~93	~20	3,434	
	4	Cr1	~121	67.5***	1,686	
	5	Cu2-1	<35	<10	287	
	TOTAL				8,476	
Unit 3 (1996)	Step No.	Step	Application Temperature	Duration (hours)	Deposit Removed (kg)	Total Waste Volume (liters)
	1	Cu1-1	<35	~8	31	~717,000
	2	Cr1	107	100-110	2,292	
	3	Cu2-1	<35	~8	204	
	TOTAL				2,527	

* For brevity, the rinse steps between the copper (Cu) and iron (Fe)/crevice (Cr) cycles and passivation steps are not shown.

** Individual steps are denoted by the type (Cu, Fe or Cr), followed by the cycle and step numbers. For example, Cu2-1 refers to the first copper step in the second copper cycle.

*** 50 hours at full height and 17.5 hours between TSP 5 and the tube sheet.

**TABLE 6 SUMMARY OF CORROSION DATA FOR BRUCE A
BOILER CHEMICAL CLEANS**

Material	Corrosion Allowance (mils)[*]	Unit 4 (1993)	Unit 3 (1994)	Unit 1 (1995)	Unit 3 (1996)	% Total of Allowance for Both Unit 3 Cleans
SA-515, Gr.70 (TSPs)	6 ^{**}	0.70	1.26	1.13	0.60	31
AISI-1018 (U-bends)	6 ^{**}	0.53	1.71	1.03	0.49	37
AISI-1015 (Internals)	27.5	2.90	2.20	1.53	0.64	10
SMAW E7018, A1 (welds)	27.5	4.20	9.70 ^{***}	6.44	3.30	47

^{*} 1 mil = 0.001 inch = 25.4 μ m

^{**} Corrosion allowance for SA-515, Gr.70 and AISI-1018 carbon steels was revised from 3.0 to 6.0 mils before the 1995 Unit 1 clean, based on Flow Induced Vibration (FIV) analysis.

^{***} Corrosion penetration for the SMAW material during the 1994 Unit 3 clean was determined from weight loss measurements performed on severely pitted coupons. Maximum pit depth was <30 mils, but inspections of boiler internal welds did not reveal localized attack as found on coupons.

TABLE 7 WATER LANCING RESULTS: 1993 - 1996

Unit (Year)	Area Lanced	Operating Pressure	Pre BOCC Lancing	Post BOCC Lancing	Key Results
Unit 4 (1993)	TSPs	10,000 psig (pump)	TSPs 3-7. Limited to areas where broached hole blockage was >40%.	Only some areas of TSP 1&2 in the west bank where broached hole blockage was up to 100%.	- Water lancing reduced broached hole blockage to 0-10% (10-20% at worst). - BOCC operations left TSP broached holes "as new" with 0-5% blockage (0-10% at worst). - Shorter magnetite step during west bank BOCC left some areas in TSP 1&2 up 100% blocked. Water lancing reduced blockage in these regions to 20% or less. - Tube land deposits left on all TSPs at the end of the cleaning operations.
	HLUBS	7,500 psig (pump)	East bank only.	East and west bank.	- Pre BOCC lancing of east bank removed some surface deposit but left hourglass areas dirty. - Post BOCC operations on the east bank left 30-60% surface exposed on the top side, compared with 60-80% on the bottom side. - Boiler 1 HLUBS left cleaner than those in Boilers 2, 3 & 4. The HLUBS in the latter boilers were left with 0-10% and 0-50% surface exposure on the top and bottom sides respectively.
	Tube Sheet	5,000 psig (nozzle) for straight-ahead and side-shooting lance 3,000 psig (nozzle) for 90° and 30°/150° barrel spray units.	Not done due to timing of containment seal installations.	East and west bank.	<u>2,201 kg</u> of tube sheet deposit removed. - Cold leg and outer hot leg central areas cleaned down to the tube sheet. - Hard tube scale left in the hot leg areas about 15-18 cm (6-7 inches) above the tube sheet. Tube sheet inspections were not possible in these regions. - Hard sludge piles were not evident in the restricted hot leg zones.
Unit 3 (1994)	TSPs	10,000 psig (pump)	East and west bank. Limited to some areas of TSP 1, 6 and 7 where broached hole blockage >60%.	Not required as determined from visual inspections.	- Combination of lancing and BOCC left broached holes virtually deposit free with 0-5% blockage (10-20% at worst). - Tube land deposits remained in most TSP areas inspected after BOCC.
	HLUBS	8,000 psig (pump)	East and west bank.	East and west bank.	- Lancing before BOCC exposed scallop bar surfaces but left hourglasses filled with deposit. - Post BOCC lancing left about 50% and 80% of surface exposed on top and bottom sides respectively. - Most hourglasses left filled with deposit at the end of lancing and BOCC activities.
	Tube Sheet	5,000 psig (nozzle) for straight-ahead lance. 3,000 psig (nozzle) for 90° and 30°/150° barrel spray units	East and west bank.	East and west bank.	- Pre BOCC lancing dislodged about <u>1,770 kg</u> of deposits, while post BOCC operations removed roughly <u>875 kg</u> of BOCC insoluble residues. - Final tube sheet condition similar to that of Unit 4 after water lancing. - Cold leg and outer hot leg areas cleaned down to tube sheet. 7.5-15 cm (3-6 inches) of hard tube deposit left in hot leg central areas.

TABLE 7 (Continued)

Unit (Year)	Area Lanced	Operating Pressure	Pre BOCC Lancing	Post BOCC Lancing	Key Results
Unit 1 (1994)	TSPs	10,000 psig (pump)	Not applicable.	Not applicable.	- Lancing of TSPs 6&7 in all eight boilers reduced broached hole blockage to 20% or less. - Water level oscillation problems temporarily relieved.
Unit 4 (1995)	HLUBS	10,000 psig (pump)	Not applicable.	Not applicable.	- Lancing of HLUBS hourglass areas, removed most of surface deposit left behind after the 1993 cleaning activities. - Hourglass areas left filled with deposit on top and bottom sides. - HLUBS visual inspections showed severe degradation in Boilers 2&7 over 2 years and relatively minor degradation in other Unit 4 boilers. - Scallop bar degradation more severe in central HLUBS areas and inside hourglass regions.
	CLUBS (Boiler 2 only)	10,000 psig (pump)	Not applicable	Not applicable	- Most surface deposit removed. - Hourglasses left filled with deposit. - No evidence of scallop bar degradation during visual inspections.
Unit 1 (1995)	TSPs	10,000 psig (pump)	East and west bank. Restricted to areas of TSPs 1-5 where broached hole blockage was >60%.	Not required as determined from visual inspections.	- Combined BOCC and water lancing operations left broached holes virtually deposit free (0-5% blockage). - Tube lands cleaned to a greater extent than in Units 3 & 4 previously. - Thin residues left in the tube land areas.
	HLUBS	10,000 psig (pump)	East and west bank.	East and west bank.	- Lancing before BOCC exposed 50-80% of the scallop bar surfaces on the top and bottom sides. - Post BOCC lancing left 80-90% of scallop bar surfaces clean on both sides. - Hourglass deposits were partially removed by crevice cleaning step. - Scallop bar degradation pattern similar to that seen in Unit 4 earlier in 1995.
	Tube Sheet	5,000 psig (nozzle) for straight-ahead lance. 3,000 psig (nozzle) for 90° and 30°/150° barrel spray units	East and west bank.	East and west bank.	- Roughly 2,000 kg of deposit dislodged before BOCC, compared with about 520 kg after BOCC. - Post lancing inspections before BOCC showed: - Cold leg and outer hot leg areas cleaned down to tube sheet. 2.5-7.5 cm (1-3 inches) of hard scale in a few cold leg areas inspected. 23-37 cm (9-15 inches) of hard tube scale in hot leg central areas. - Similar inspection results after post BOCC water lancing except height of hard tube scale reduced by 2.5-10 cm (1-4 inches) in 6 of 8 boilers.

TABLE 7 (Continued)

Unit (Year)	Area Lanced	Operating Pressure	Pre BOCC Lancing	Post BOCC Lancing	Key Results
Unit 3 (1996)	HLUBS	10,000 psig (pump)	East and west bank.	East and west bank.	- Pre BOCC lancing exposed 70-100% scallop bar surface on both sides. - Inspections done after BOCC and water lancing showed: 90-100% surface exposure on the top and bottom sides. - Hourglasses were nearly deposit free with faint residues left behind.
	Tube Sheet	5,000 psig (nozzle) for straight-ahead lance. 3,000 psig (nozzle) for 90° and 30°/150° barrel spray units	East and west bank.	East and west bank.	162 and 46 kg removed before and after BOCC respectively. - Post lancing, pre BOCC condition was virtually identical to "as left" state in 1994. - Inspections after BOCC and lancing showed the height of hot leg tube scale was reduced by 2.5-10 cm (1-4 inches) in 7 of 8 boilers. - Hard sludge piles up to 8 cm (5 inches) high were observed in some hot leg areas previously inaccessible due to tube scale.

FIGURE 1

CUTAWAY VIEW OF A BRUCE A BOILER

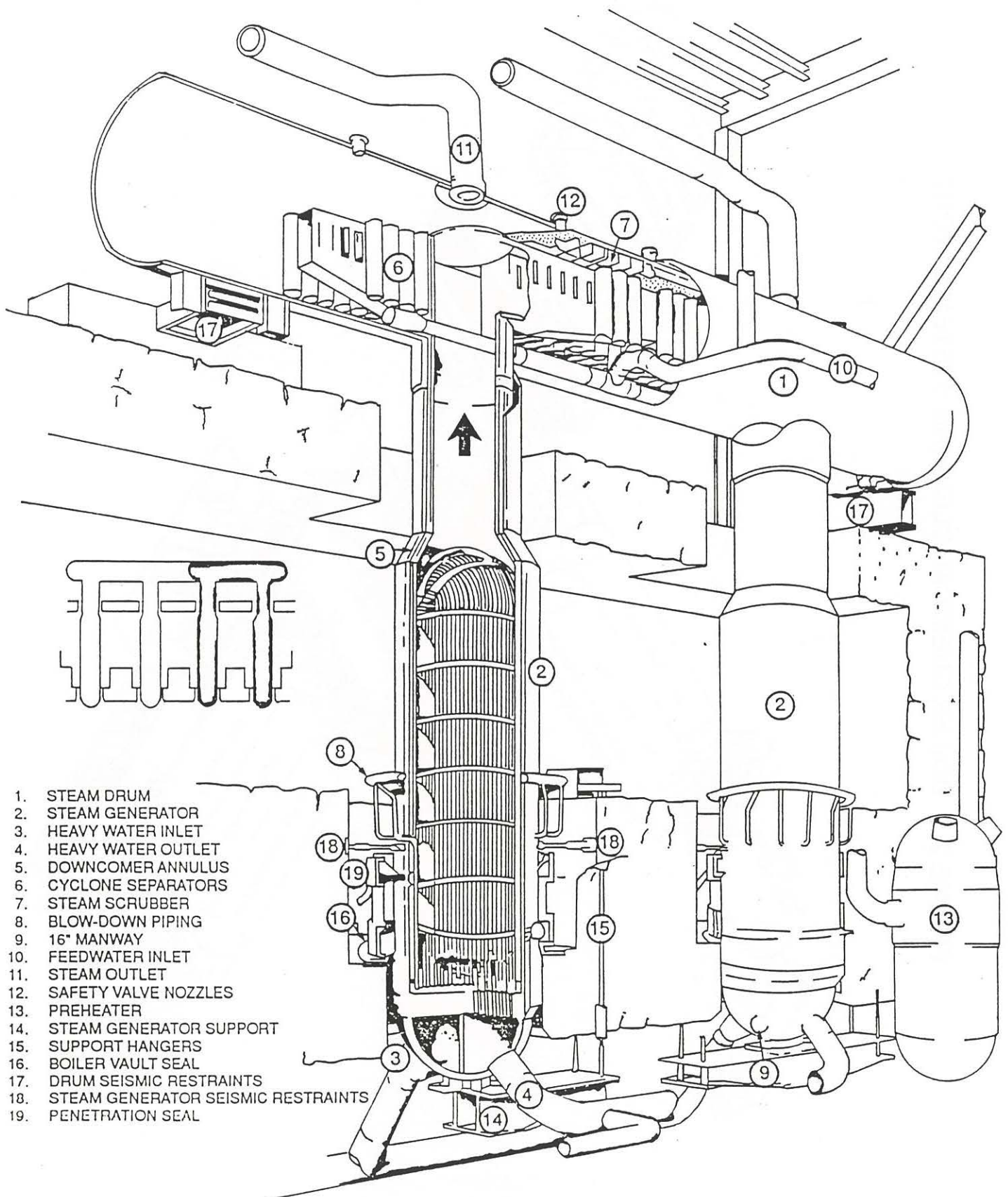
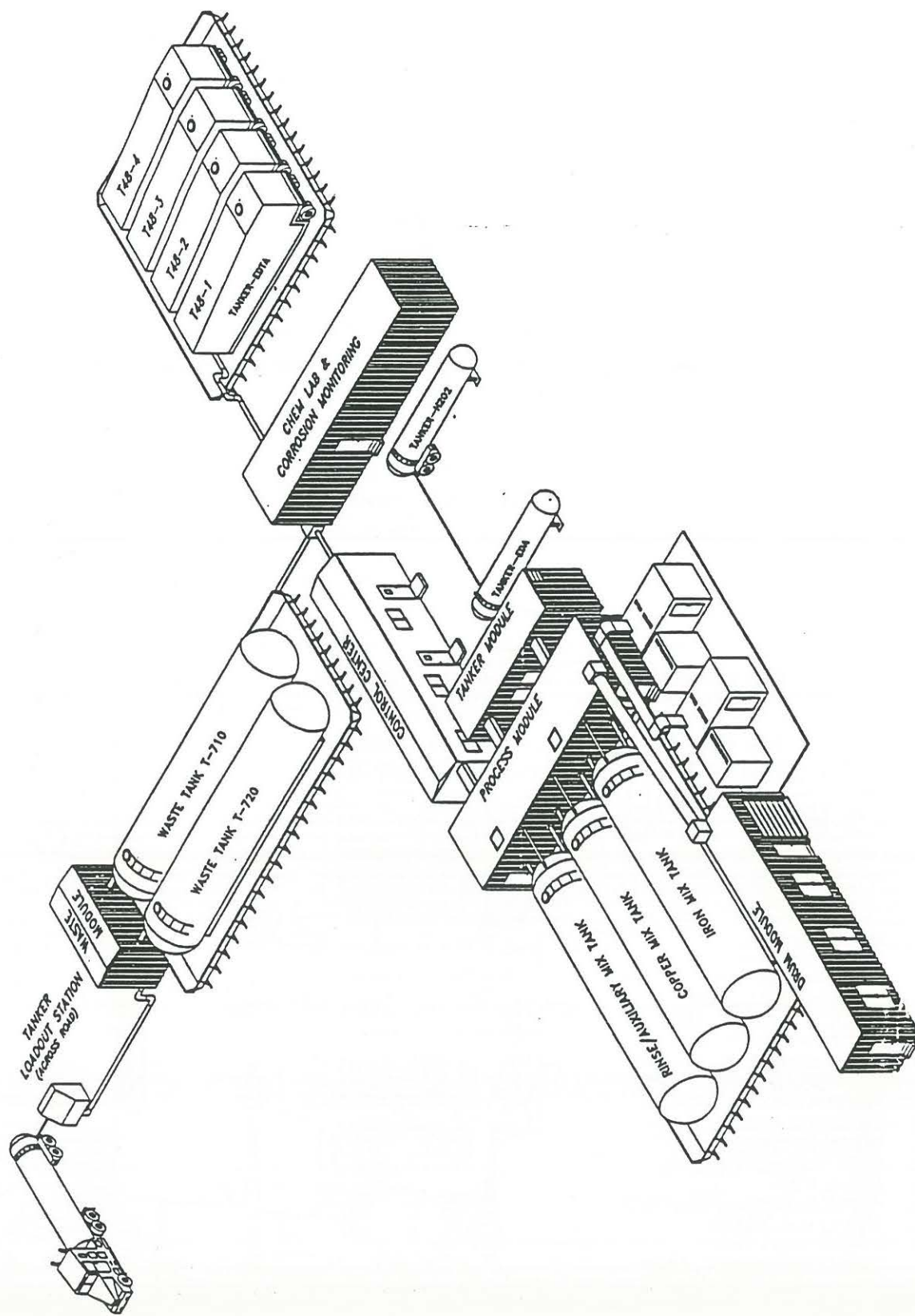


FIGURE 2 BOILER CHEMICAL CLEANING SYSTEM LAYOUT



FLOW DIAGRAM FOR BOCC SYSTEM COMPONENTS INSIDE THE POWER HOUSE

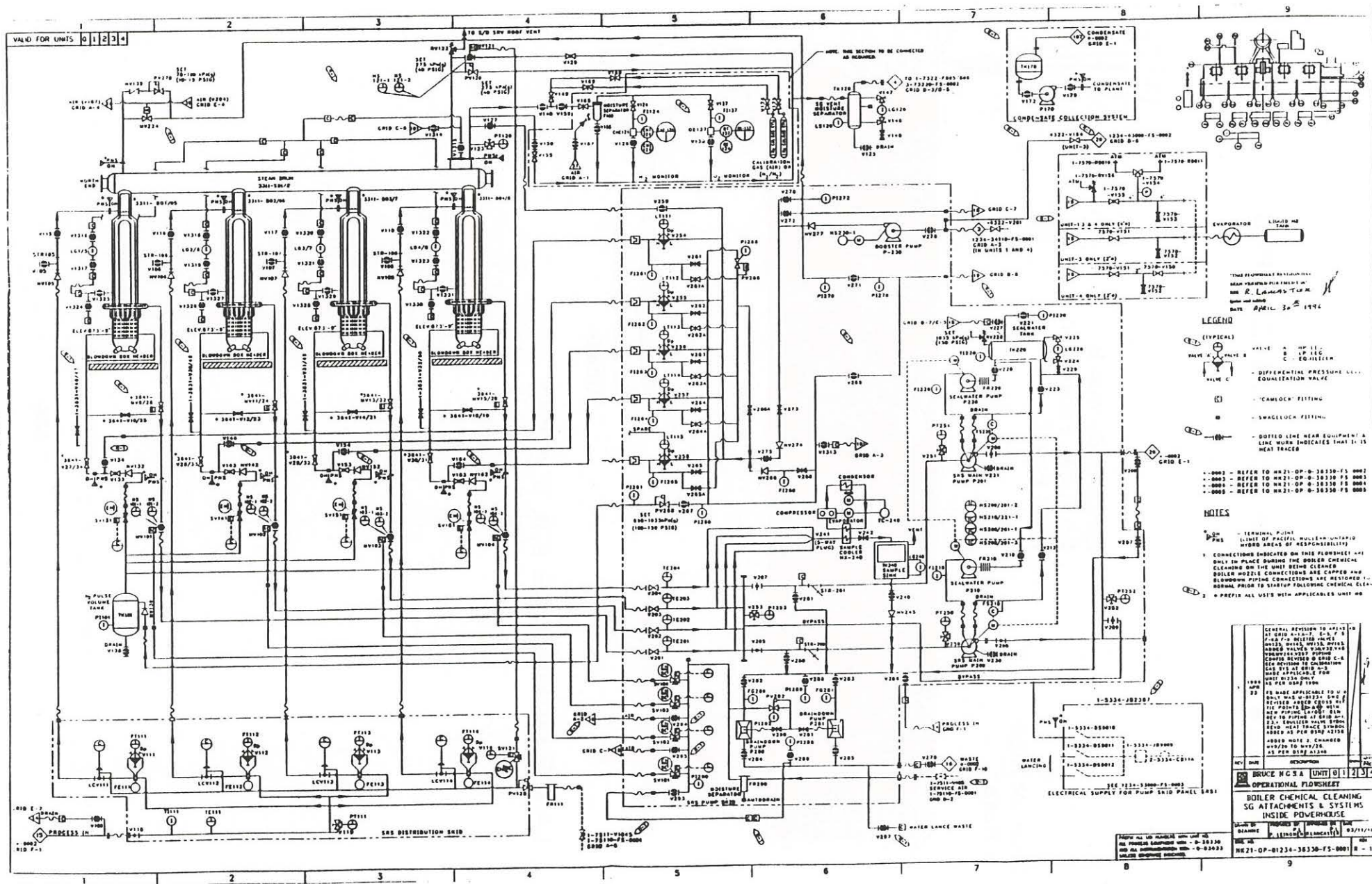
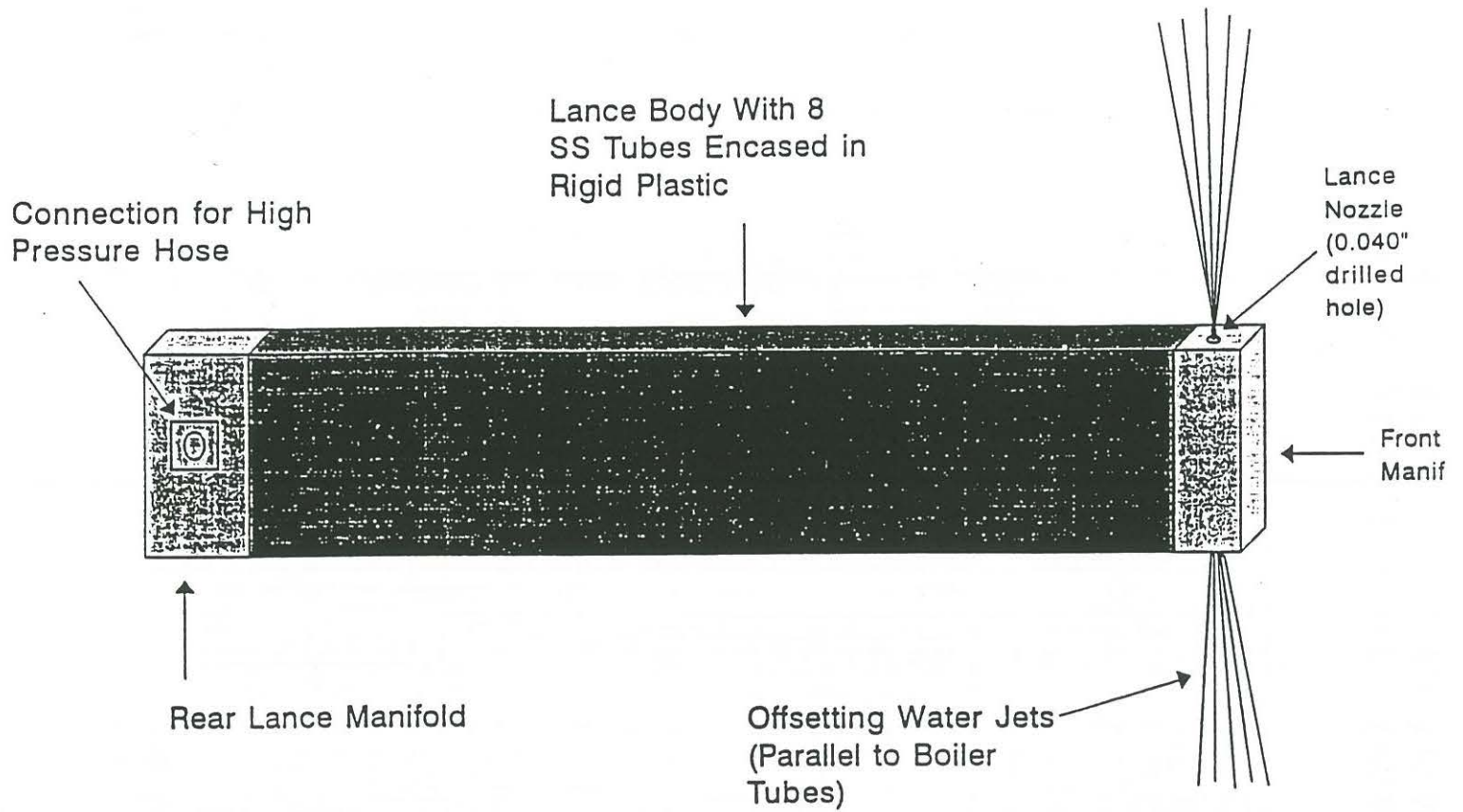


FIGURE 4

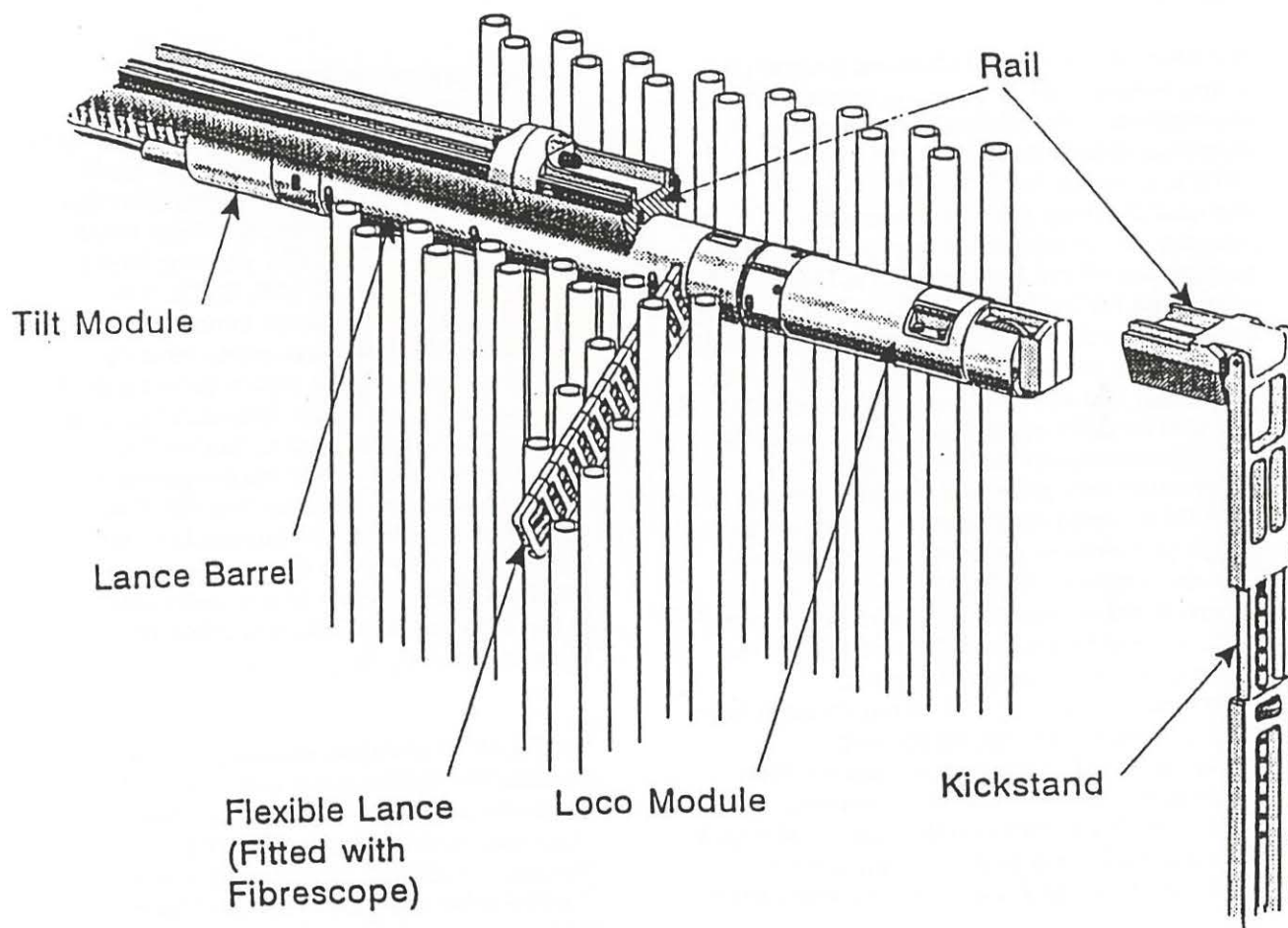
TSP LANCE DESIGN FEATURES



TYPICAL LANCE DIMENSIONS: 9 ft, 6 in long.
0.115 in thick
1.5 in wide

FIGURE 5

CECIL® TUBE SHEET LANCING COMPONENTS
INSIDE THE STEAM GENERATOR



From Reference 9