STEAM GENERATOR DESIGN FOR ACR-1000

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ABSTRACT

Babcock & Wilcox Canada (BWC) has developed a preliminary design for an advanced recirculating steam generator (RSG) to meet the Atomic Energy of Canada Limited (AECL) design requirements for the Advanced CANDU reactor (ACR-1000) steam generators. In addition to fulfilling all thermal hydraulic requirements, the ACR-1000 advanced RSGs offer improved reliability by addressing all degradation problems known within the industry. The ACR-1000 RSG design builds upon BWC's long history of steam generator design and manufacturing experience which includes 247 steam generators for CANDU nuclear systems and 42 replacement steam generators for US PWR nuclear power plants.

The ACR-1000 RSG features an optimized Alloy 800 tube bundle that satisfies all heat transfer requirements with plugging and fouling margin and is arranged within the pressure boundary such that flow resistances are minimized. Taking advantage of BWC's exceptional performance history with integral preheaters, the ACR-1000 RSG will have an advanced preheater to minimize tube bundle size and cost.

Lattice grid tube supports and flat bar U-bend restraints provide effective structural support for the tube bundle and prevent damaging flow induced vibration. The overall tube bundle arrangement maximizes secondary side circulation which benefits steam generator deposition, hydraulic stability and operating characteristics. Proven high efficiency steam separators, providing high quality steam to the turbines, are arranged within the steam drum such that all water level control requirements are satisfied. In-service inspection and maintenance is facilitated by carefully positioned access openings. The steam generator includes features to control tube bundle deposition. These features and advanced materials qualify the ACR-1000 RSGs for an extensive design life.

1. Introduction

Babcock & Wilcox Canada (BWC) has developed an advanced steam generator design for the ACR-1000[1] (Advanced CANDU Reactor 1000) to meet the performance and reliability requirements of Atomic Energy of Canada Limited (AECL). The ACR-1000 steam generator (SG) is an extension of BWC steam generator design experience gained from the design and manufacture of 289 steam generators for both CANDU and PWR reactor systems (Table 1). The standard ACR-1000 plant is a two-unit, integrated plant with each unit having a nominal gross output of about 1165 MWe with a net output of approximately 1085 MWe. The reactor units use modular horizontal fuel channels surrounded by a heavy water moderator which is typical of CANDU reactors. The ACR-1000 system however uses low enriched uranium fuel and light water coolant which is a new innovation relative to previous CANDU systems which use heavy water as the reactor coolant fluid. The light water coolant in the ACR-1000 design transfers heat to the secondary steam side through four advanced recirculating steam generators for each reactor unit. These steam generators have been designed by BWC to integrate proven design features such as lattice grid tube supports, flatbar U-bend restraint systems, high efficiency moisture separators and an integral preheater while offering material advances and improved inspection and maintenance features. This paper describes the features of the BWC ACR-1000 steam generators.

2. Design Process for ACR-1000 Steam Generators

As described in "Steam Generator Design Requirements for ACR-1000[2]" the system design optimization requires analysis of maximum channel power levels, fuel cooling safety margins, Heat Transport System (HTS) pressures, HTS flow rates, of overall thermal cycle efficiency and net electrical output.

These system wide considerations also affect the design and sizing of the ACR-1000 steam generators. Consequently, BWC was integrally involved in sizing the ACR-1000 steam generators as the system process conditions evolved. As with most other CANDU steam generators a design using an integral preheater is required, given the low HTS cold leg temperature, high steam pressure and overall demanding heat transfer requirements. To maintain a steam generator size within the proven experience of BWC, four steam generators rather than two per reactor unit were selected. The ACR-1000 steam generators have a heat transfer area of 8454 m^2 (91,000 ft^2) using 7234 Alloy 800 tubes having a nominal outside diameter of 17.46 mm (11/16") and a tube wall thickness of 1.07 mm (0.042"). The overall arrangement of the ACR-1000 steam generators is illustrated in Figure 1. This design size is within BWC's experience which includes large replacement steam generators for CE System 67 units. A comparison between these PWR steam

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[1] ACR-1000™ (Advanced CANDU Reactor™) is a trademark of Atomic Energy of Canada Limited (AECL)

[2] Steam Generator Design Requirements for ACR-1000, Shankar Subash, Ken Hau, 5th CNS International Steam Generator Conference, Nov. 2006.

generators, as well as other recent CANDU steam generators, to the ACR-1000 steam generators is provided in Table 2.

The design process used by BWC to design replacement steam generators includes input from various groups throughout The Babcock & Wilcox Company, and draws from the experience of over forty years of nuclear steam generator design and fabrication. This experience, as summarized in Table 1, entails both CANDU steam generators and replacement steam generators which covers numerous tubing materials, tube support systems and evolutions in steam separator technologies. The best of this experience has been brought together into the ACR-1000 steam generator design.

The engineering of steam generators requires the integration of multiple design criteria including industry codes and standards, customer specification requirements, and BWC design requirements. When applying so many criteria, design optimization must be performed in order to satisfy all requirements to the maximum extent possible. The ultimate goal of the design process is to yield a steam generator design which:

i) meets or exceeds all BWC and customer specified requirements,

ii) is based on sound engineering principles supported by successful operational experience and laboratory research and development,

iii) satisfies all required codes and standards,

iv) has enhanced reliability.

3. Thermal Sizing and Performance

The tube bundle is sized based on the performance requirements as specified in Table 3.

The bundle sizing parameters listed in Table 3 essentially list the minimum inputs required to size the tube bundle heat transfer area. Using the overall heat transfer rate and by performing heat balances on both the primary and secondary sides all inlet and outlet thermal differences can easily be determined. The tube bundle surface area is then sized using the BWC one-dimensional, thermal hydraulic computer code 'CIRC' to satisfy these terminal point conditions. The thermal performance code 'CIRC' has been the principal design tool for recirculating nuclear steam generators at BWC for over twenty five years and has been proven to be very accurate in predicting operating steam generator performance.

It is interesting to note that the primary side outlet temperature (reactor cold leg temperature) needed to satisfy the heat balance is 274.1°C (525.4°F) which is colder than the saturated steam temperature in the tube bundle which is 276.3°C (529.4°F). This reverse temperature gradient at the outlet of the steam generator forces the use of an integral preheater within the ACR-1000 steam generator. With an integral preheater the cold 215°C (411°F) feedwater is used to drive the primary outlet temperature down to 274.1°C (525.43°F) through subcooled boiling and convective heating of the feed flow within a baffled preheater.

Baffled preheaters have been used with 158 CANDU steam generators representing the vast majority of CANDU steam generators. These preheaters have performed exceptionally well with no tube plugging associated with preheater design. The ACR-1000 SG preheater will maintain the successful design of these earlier units in that a tie rod supported baffled arrangement will be used to promote effective cross flow induced convective heat transfer while minimizing pressure drop. The preheater arrangement provides effective venting and eliminates stagnation zones that could possibly trap steam and cause steam collapse structural loads.

The preheater arrangement uses erosion-corrosion resistant steel for the boundaries of the flow channels and distribution box that route feed flow into the preheater zone from the feedwater nozzle. Drilled tube support baffle plates with cut out flow windows are fabricated from 410S stainless steel.

The ACR-1000 SG does include a new preheater design innovation in that the traditional thermal plate which separates the lower end of the preheater zone from the top of the tubesheet has been eliminated. The ACR-1000 preheater arrangement is situated directly on top of the cold side of the tube sheet with no thermal buffer zone. Elimination of the thermal buffer zone below the thermal plate reduces the tube bundle size. Improved finite element modeling tubesheet thermal stresses resulting from cold feedwater flow has made it possible to eliminate the thermal plate.

One potentially negative consequence of this arrangement is that recirculated fluid from the steam separators is no longer able to get to the hot leg by flowing below the thermal plate, across the top of the cold side of the tubesheet, and enter into the hot leg by crossing the tube free lane. Lowering the preheater eliminates this flow path, potentially reducing flow to the hot leg, reducing circulation, increasing hot leg boiling and increasing hot leg deposits. To eliminate this potential concern, BWC has added an innovative flow slot to the back side of the preheater as illustrated in Figures 2 and 3. This downcomer flow slot is situated between the preheater divider plate and the hot leg tube bundle and directs some recirculated flow to the tube free lane between the preheater zone and the hot leg bundle. From the tube free lane, recirculated flow enters the back side of the hot leg just as it did with the earlier thermal buffer zone.

4. ACR-1000 SG Circulation Ratio

One of the most important design criteria for nuclear steam generator thermal hydraulic design is circulation ratio. Circulation ratio is defined as the ratio of two phase mass flow rate through the tube bundle versus the steam outlet flow rate. Based on this definition the average steam quality leaving the tube bundle is the inverse of the circulation ratio. A steam generator with a high circulation ratio maintains a large quantity of liquid flowing through the tube bundle relative to steam output. Therefore, the amount of steam within the tube bundle fluid is small for a high circulation ratio.

By maximizing the circulation ratio, problems attributable to tube dry-out, tube degradation, poor heat transfer, corrosion product transport, sludge management, and water level controllability, all of which combined or individually have historically contributed to poor performance and premature failure, are alleviated. BWC has consistently used a philosophy to design steam generators with high circulation ratios, while carefully analyzing all internal components to provide a design which prevents excessive tube motion due to flow induced vibration.

The ACR-1000 SGs are designed to have as high a circulation ratio of as possible in compliance with the AECL Technical Specification and the BWC design philosophy.

In order to achieve a high circulation ratio within a steam generator, it is important that the various internal components within the steam generator that impede the circulation flow are designed to provide minimal resistance. BWC has maintained ongoing research and development in order to optimize the pressure drop characteristics of the major components within the steam generator.

The lattice grid design provides minimum resistance to fluid flow by having a very open structure, with minimal blockage of flow. Numerous full scale fluid flow tests have been performed to determine and verify the pressure response to fluid flow. Figure 4 compares the pressure loss factor for a broached plate and lattice grid as a function of pitch/diameter ratios. For the ACR-1000 pitch to diameter ratio of 1.42, lattice grids have a significantly lower pressure drop than broached plates.

The U-bend design also offers minimized resistance to fluid flow. The staggered fan bar assembly design does not create a "wall like" structure to inhibit the flow of fluid. Further, the fan fingers are designed to align with the 3-D thermal hydraulic analysis predictions of the fluid flow direction within the U-bend. Fan bars are oriented parallel to the flow as much as possible to minimize the U-bend support pressure drop. The primary moisture separator design has also been optimized to reduce pressure drop thereby enhancing circulation.

The primary objective of a high circulation ratio is to avoid high levels of steam in the steam-liquid mixture flowing through the tube bundle. Steam quality is defined as the mass of steam to the total mass of the mixture (steam plus liquid). Local areas of dry-out (caused by high steam quality) are detrimental to tube reliability since these areas accumulate deposits resulting in increased susceptibility to tube degradation.

Deposits occur in regions of dry-out or high steam quality because liquid transported contaminates are precipitated out of the liquid during the phase change to steam. A high circulation ratio maximizes the availability of liquid mass recirculating within the tube bundle and minimizes the potential for tube surfaces to experience dry-out and accumulate deposits. When deposits form on the steam generator tubes, the deposit acts as an insulating material which increases the temperature of the outer surface of the tube. They also form crevices where aggressive chemical conditions can develop. Therefore, by maximizing circulation ratio, the possibility of dry-out due to high steam quality and the resulting deposition which causes tube degradation is reduced.

The technical paper, "Reducing Tube Bundle Deposition with Alternative Amines" jointly issued by AECL and EPRI at the Third International Steam Generator and Heat Exchanger Conference, June 1998 provides experimental results confirming increased deposition with increased steam quality (i.e. reduced circulation ratio). The test results indicated a notable increase in deposition with increasing quality between 30% and 50% quality. Above 50% quality, a very abrupt increase in deposition is observed.

A high circulation ratio also maximizes the available fluid mass and fluid velocity in the region above the tubesheet. By maximizing circulation ratio, the velocity of liquid mass across the tubesheet at the secondary face is high thereby reducing areas of low velocities and high steam quality. World wide operating experience has shown that steam generators with low circulation ratios routinely experience large levels of sludge deposition and sludge pile formations on the top face of the tubesheet.

A high circulation ratio also has many benefits opposite the controllability of the operating steam generator. The resultant high liquid to steam mass ratio within the riser region provides for a steam generator design that is least affected by water level swell and shrink during transients. Swell is the phenomenon of rapid steam creation during power increases or pressure decreases which causes the overall water level to rapidly rise while maintaining a relatively constant secondary side mass. Shrink is the opposite phenomenon; where steam is rapidly condensed or compressed (i.e. as with cold feedwater injection or pressure increase) and the water level within the steam generator rapidly falls. By maximizing the amount of liquid phase within the steam generator, the magnitude of the swell and shrink effects can be minimized.

Water level stability is also a critical consideration for an operating steam generator. Even during steady state with no changes in pressure, power or feedwater conditions, steam generators may experience "two phase boiling instability" which causes large oscillatory changes in water level. This instability can be attributed to a high pressure drop in the riser and / or a low pressure drop in the downcomer and bundle entrance area due to low liquid velocities. By maximizing circulation ratio, the margin to the onset of instability is maximized.

5. Lattice Grid Supports

The design of the ACR-1000 tube support system is critical to the reliability of the tube bundle and the steam generator. BWC has selected the lattice grid as the optimum choice for the ACR-1000 SGs. The design features of lattice grids in terms of construction, material, thermal-hydraulics, and mechanical strength are discussed to demonstrate their effectiveness in optimizing flow characteristics while providing high strength. Lattice grid supports in the ACR-1000 SGs are a continuation of a long successful history using lattice grids which includes 126 recirculating steam generators.

The design requirements for the lattice bar tube supports are as follows. The support must:

(a) Preclude excessive Flow-Induced Vibration (FIV).

(b) Minimize pressure loss in order to promote high circulation ratios which result in sweeping flows.

(c) Provide line support contact to reduce the potential for deposition of corrosion-causing impurities and localized dryout.

(d) Provide sufficient tube contact length to lower contact stress and hence minimize fretting wear of tubes.

(f) Accommodate tube/support motions during heatup/startup operation without risk of lockup and without the need for tie rods.

(g) Resist corrosion and stress corrosion cracking due to normal operation and chemical cleaning.

(h) Provide a strong tube support design to withstand accident loads (seismic, MSLB, LOCA) without the need for tie rods and with no tube crush penalty

(i) Withstand handling loads.

Figures 5 and 6 show the details of a typical lattice grid. The lattice grid is made up of a series of high bars (approximately three inches in width) oriented at 30° and 150° to the tube free lane and located every four to eight pitches, depending on the size of the bundle and the particular steam generator loading conditions. High bars are spaced every six pitches. Low bars (one inch in width) are located at every pitch location between the high bars. All low bars flush to the top of the high bars are oriented at 30° to the tube free lane and all low bars flush to the bottom plane of the high bars are oriented at 150° to the tube free lane. The bar ends are fitted into precise slots of a specially designed peripheral support ring, which is then sandwiched by two outer retainer rings. The outer retaining rings of the assembly are lock welded together. To further enhance stability of the grid, tube free lane support beams and span-breaker bars are secured on the upper and lower surface of the grid.

Lattice supports are positioned within the steam generator shroud at selected elevations to prevent excessive FIV as discussed below. On assembly, the complete lattice grid is positioned within the shroud using shear blocks and wedge blocks around the periphery. Shroud pins positioned between the wedges stabilize the shroud within the secondary shell.

The tubes are held in position within the diamond-shaped bar openings which provide line support contact. This minimizes the area of crevices between the tubes and bars, which could trap corrosion products, and thereby eliminates the formation of any stagnant spots responsible for dry-out caused by local superheat. It is well known that deposits rapidly initiate at the sharp edge entrance region of the broached lobes in a broached plate TSP due to rapid changes in flow area and hence flow velocity. Once deposition initiates in the narrow flow lobes of this design, the problem is further aggravated as deposition further reduces the available flow area. The lattice grid tube support does not have such severe changes in upward flow area, due to the open flow design, and the lattice bars (high bars and low bars) all have rounded edges, to minimize stagnation regions and potential sites for deposit initiation.

Type 410S stainless steel was selected for all tube support material in contact with the tubes, which includes lattice bars, U-bend flatbars and preheater baffle plates. Material selection started in 1980 when BWC evaluated available information and conducted an extensive corrosion program characterizing a wide range of tube support materials. This work was aimed at selecting the material(s) which best resisted the tube denting phenomenon in nuclear steam generators while providing high strength and a compatible coefficient of thermal expansion.

Type 410S material exhibits very good corrosion resistance and considerable pitting resistance in steam generator secondary side environments. It also exhibits zero change in volume of the adherent oxide versus the metal corroded. Type 410S material has compatible expansion properties with carbon steel so that the risk of bar buckling caused by differential expansion between the bar and peripheral ring is eliminated.

The ACR lattice grid design provides a very open structure to the fluid flow. The open geometry is made possible by running low bars at two different levels with a one inch gap in between. The tubes are, in fact, held within parallel bars with two line support contacts at any horizontal plane of low bars. As a result, the free flow area per tube at each support plane is considerably higher than for a typical broached plate design. The ACR lattice grid has a flow area equal to 66% of the approach flow area in the bundle. This type of structure represents a high porosity to the two-phase fluid flow. The high porosity significantly lowers the pressure head loss across the lattice grids and promotes a high circulation ratio within the steam generator.

The lattice tube support structure has been carefully designed to establish adequate mechanical strength to handle various types of loads related to handling, shipping, operation, seismic conditions and burst pipe events in order to ensure the safety and reliability of the steam generator.

The lattice grid construction is designed to withstand severe in-plane loads during a seismic or burst feedline event and out-of-plane loads during a main steam line break event. In-plane load cases include lateral seismic loads in two directions, burst feedline loads and handling and shipping loads.

The in-plane loads which originate from tubes are first distributed onto the low bars. Loads from a group of low bars are then transmitted to the interlocking high bars which carry these loads axially to the peripheral ring. From the ring, loads are carried via the lattice centering wedges to the shroud and through the shroud pins to the shell.

Out-of-plane forces are generally caused by friction when tubes slide vertically on the support due to expansion, and by pressure drop from fluid forces across the grid during operation or a burst steam line event. Pressure drops are comparatively small because of the open geometry of the lattice grid and sliding friction forces are low since lateral forces are small during normal operation. When subjected to upward flow loading, the low bars, which cross on the bottom of the lattice grid assembly are pushed into the high bar slots; consequently, the high bars support the lower low bars; a beam across the tube free lane which is welded to the outer retainer rings, resists the upward motion of the upper low bars. The high bars are inherently strong in the vertical direction since they carry vertical loads about their strong bending axis.

The lattice supports are positioned to avoid excessive FIV at the tubesheet level flow entrance region. (There is little excitation in the rest of straight spans.) The lower lattice support is positioned relatively close to the tubesheet to reduce this critical span as well as to keep the flow from spreading vertically before it penetrates deep into the bundle. The positioning of the tube supports is verified by FIV analyses addressing fluid-elastic instability, response to turbulence excitation and vortex shedding resonance.

6. U-Bend Supports

Flatbar U-Bend Restraints (FUR) have been used by BWC in 78 recirculating steam generators. FURs provide effective, close clearance supports of all U-tubes at closely spaced intervals by 410S stainless steel flat bars. The support configuration is open to flow, is upwardly vented and has line contact support at all locations in the bundle so that no area will entrap vapour or build up contaminants.

Tube wear has not been observed in the most recent CANDU Flatbar U-bend Restraints at Wolsong, Cernavoda and Qinshan which is testimony to the effectiveness of the design in preventing wear. This same successful design is incorporated into the ACR-1000 SGs with one evolutionary improvement: a reduced tube to support bar diametrical clearance of 0.002 inches.

The BWC Flatbar U-bend Restraint system for a replacement steam generator has fan assemblies on each side of the tube bundle center line to provide U-bend support locations. Each fan assembly includes a number of flatbars. The flatbars in the fan assembly are arranged to provide the following U-bend support features:

- Figure 7 shows fan assemblies having four flatbar fingers positioned on each side of the bundle centerline. A pair of fan assemblies is positioned between each layer of tubes. The fan assemblies stagger in and out from tube layer to tube layer so that no tube is contacted on directly opposite sides by a flatbar (Figure 8). This minimizes the resistance to flow through the U-bends and improves the circulation ratio.

- Each fan assembly consists of a flatbar fingers that are connected at their lower end by a connector bar. For example, the fan assembly shown in Figure 8 has four flatbars that are connected at their lower end by a fifth flatbar (connector bar). The connection between the four flatbars and the fifth flatbar is an autogenous full penetration heat treated weld.

- The flatbars in a fan assembly are positioned so that all U-bends are supported at close intervals.

- All U-bends are supported directly by a flatbar of the fan assembly including the smallest radius U-bend.

- The bars are of Type 410S precision, cold rolled material. The 410S material provides resistance to fretting wear, excellent strength and high resistance to corrosion related tube denting.

- The U-bends are assembled with tight clearances, with a nominal tube to flatbar diametral gap of 0.002".

- The bars have a generous width so as to distribute contact force and to minimize the possibility of fretting.

Free expansion of the U-bend during operation is essential in order to avoid tube stress or damage. The FUR system allows free expansion of the U-bend tubes without the need for sliding between tubes and bars. This is achieved by supporting the FUR assembly from the outermost layer of tubes and by avoiding other restraint points. In this way the FUR assembly and U-tubes move up and down together on heatup and cooldown and also during operation at power when tube hot legs and cold legs have slightly unequal leg temperatures.

Prevention of excessive FIV and fretting wear is a primary objective which is achieved as follows.

The basic positioning of the FUR bars is arranged to conservatively meet the design limits established for fluid elastic instability and for response to random turbulence.

A 3-D flow distribution analysis is performed to derive a detailed flow distribution in the U-bend area. From this analysis, velocity and density profiles are determined for each of the most critical "longest" span cases (i.e. longest with four, three...one supports).

Each of the "longest" tubes is modeled by finite elements to provide the various mode shapes and frequencies. The structural modes along with cross flow hydraulic loads are assessed for FIV and wear using linear and non linear analysis of various clearances.

U-bend support clearances are selected to achieve the lowest practical clearances while avoiding problems due to tube / bar interference i.e. marking of the tubes by the bars, splaying of the bundle due to bar tolerance accumulation, buildup of bundle thickness as tubing progresses, etc.

A nominal support clearance of 0.002 inches assures with a high level of confidence that all supports will be effective in minimizing tube vibration and minimizing tube wear.

The optimum range of flatbar U-bend support clearance was verified by early air flow tests which showed that flatbars with .003" to .010" clearances were more effective than the scalloped bar design with .020" clearance i.e. the flatbars suppressed instability and in-plane motion more effectively than the scalloped bars. The test also showed the importance of small clearances which have been made possible by tighter flatbar thickness and tube diameter tolerances in the ACR-1000 SG design.

7. Separator Technology

BWC continues to be a world leader in steam/water separation technology; developing dependable, maintenance-free, high-performance separation equipment since the mid-1930's.

One of the most distinct features of the BWC separator is its extremely low moisture carryover (MCO). Moisture carryover is a measurement of the moisture exiting the secondary cyclone and is used as an indicator of dryness of the exiting steam. The units for moisture carryover are indicated as a percent by weight of the total steam flow. Table 4 provides startup MCO measurements for the BWC replacement steam generators confirming MCO well below 0.10% which complies with the ACR-1000 design requirements. Low MCO has resulted in surplus MWe output and hence increased revenue for the utilities.

The ACR steam separator system utilizes curved-arm primary (CAP) separators in conjunction with secondary cyclone separators; both of which are centrifugal type separators. The majority of the water is separated in the primary stage of separation, resulting in an inter-stage quality greater than 95%. The remaining water is then removed in the secondary stage of separation. The relatively small size of the separators allows for more efficient use of space in the drum and allows full scale laboratory testing of a single separator pair, which facilitates design optimization and confirmation testing at operating conditions.

7.1 Primary Separator

Figure 9 illustrates the primary and secondary separators. The primary separator is a relatively simple design, consisting of a 6-3/8" diameter riser, four sets of curved-arms, and an outer return cylinder. The steam/water mixture exiting the tube bundle enters the primary riser at the bottom of the support deck. From there the mixture enters the curved-arms where the majority of the centrifugal separation occurs. During the separation process, a film of water develops on the inner wall of the return cylinder and spirals down to the main inventory of water for recirculation. The return cylinder extends above the top of the curved-arms where there are several small diameter perforations and a retaining lip, which are used to improve the water removal capabilities of the separator at high steam and water flows. The steam exits the top of the primary separators into the interstage region, which is used to more evenly distribute the steam prior to entering the secondary cyclones.

The CAP primary separator has several advantages. The first is that the primary separator is highly efficient, providing a steam/water mixture to the secondaries with greater than 95% quality. This allows minimization of the interstage region and eliminates the need for a large volume for natural separation to occur. A second advantage of the CAP primary separator is that the separation process occurs in the region of the curved-arms, which remain above the drum water level during operation. This localized separation far above the primary separator deck makes the separator performance insensitive to water level thereby allowing a higher water level and a larger driving head in the downcomer. This increased driving head provides a higher circulation ratio, reducing the corrosion risks associated with high tube bundle quality and deposition. Another advantage is the relatively large flow area through the curved-arms which eliminates the need for periodic cleaning since there are no narrow flow passages which could attract deposits. The result is a low-pressure drop, high performance separator that will have a long-life of maintenance-free service.

7.2 Secondary Cyclone Separator

The secondary cyclone separator also operates on the principal of centrifugal separation somewhat similar to the primary separators. The secondary cyclone design is not limited by velocity because the water is centrifugally separated; allowing a much higher steam flow capacity per unit area. The steam enters the cyclone through tangential inlet vanes at the bottom of the cyclone which impart a centrifugal loading to the steam. Any liquid remaining in the steam is then forced to the inner wall of the cyclone where it is separated centrifugally through exit vanes. Water separated from the secondary cyclone then drains back to the main steam drum inventory for recirculation. The cyclone outlet can be sized to impose the desired pressure drop (typically about 2.0 psi) for redistributing flow within the interstage spacing.

7.3 Separator Performance

The steam/water performance of a primary and secondary separator pair has been extensively evaluated by laboratory tests, including: pressure drop, moisture carryover, operating pressure sensitivity, water flow sensitivity, water level sensitivity, and steam carryunder.

The low pressure drop across the CAP primary separator contributes to the high circulation ratio capability in the BWC steam generators. Figure 10 illustrates a circulation ratio curve and circulation flow rates for a typical BWC unit. At low steam flows, the circulation ratio is very high, but drops off with increasing flow. The water flow, however, begins very low but becomes approximately constant from about one-third load to full load. For testing purposes, the circulation ratio is held constant at steam flows above 100 percent load; a very conservative assumption.

Figure 11 illustrates the moisture carryover performance versus steam flow for a separator pair at a saturation pressure of 880 psia and under typical power series test conditions. A power series test is one which follows the typical operating conditions for the unit (see Figure 10) up to 100 percent steam flow, at which point the circulation ratio remains constant. In this case the circulation ratio was held constant at 6.0. As shown in Figure 11, the moisture carryover remained well below 0.10 percent by weight over the entire range of tested flows.

In addition to moisture carryover testing, the BWC separators has been proven to be insensitive to operational pressure, water flow and water level. Insensitivity to water level is highly desirable since the ACR-1000 SGs must accommodate large water level changes resulting from operation with a constant inventory despite rapid power changes. The swell in water level is indicated on the ACR-1000 SG illustration in Figure 1.

8. BWC Steam Drum Sludge Collection System

The ACR SGs contain a steam drum sludge collection system to be installed on the top of the primary separator deck support. The primary separator deck consists of a flat horizontal plate that supports the primary separators. The primary separator deck is stiffened in the out-of-plane direction, for normal and accident loading, by horizontal stiffeners between every second row of separators (see Figure 12). Field observations made during secondary side visual inspections of BWC steam generators report that deposition occurs preferentially in low flow regions and regions of recirculating eddies on the top of the primary deck. The highest concentration of impurities in the recirculated water occurs on the primary deck; as a result, the top of the primary deck is a logical location to include a sludge collection feature.

The sludge collector design consists of the following basic additions to the standard BWC primary separator deck design;

- Addition of a peripheral ring plate to the primary deck
- Addition of a top plate covering the stiffeners and peripheral ring plate

The basic sludge collector design is illustrated in Figure 12.

The sludge collector is designed to bleed approximately 1% of the recirculated flow from the primary separators. This represents approximately 5% of the steam flow. The flow enters the sludge collector through central annular openings around a few primary separators closest the centre-line of the steam generator. The flow exits the sludge collector through openings in the peripheral ring. Upon entering the sludge collector, the flow area greatly expands, resulting in low velocity flow which promotes the settling of particulate materials from the flow stream.

A 3-D CFD analysis of the sludge collector design has been conducted to investigate the flow fields within the sludge collector and to optimize the size, shape and location of the various flow openings and stiffeners. Figure 13 illustrates the model. Figure 14 shows the velocity profile above a standard primary deck. Figure 15 and 16 illustrate the resultant flow with a sludge collector. As shown in Figure 15, the flow enters through annular openings around a few primary separator riser pipes at the centre of the steam generator. The central-most stiffener effectively distributes the flow across the width of the sludge collector and reduces the flow velocities below 0.5 m/s in almost all of the regions of the sludge collector. The flow slowly migrates across the stiffeners to the peripheral exit holes, where the flow joins the downcomer flow.

In addition to flow simulations, simulations were performed to track the motion and settling of one and ten micron diameter particles, which are the typical size of steam generator sludge particles. These studies have shown that the efficiency of particle sedimentation within the sludge collector is between 68% to 74% and increases with particle size.

The impact of the sludge collection region on overall steam generator fouling trends was assessed by AECL using the AECL developed SLUDGE code. This analysis shows that with a sludge trap efficiency of 75% and 1% blowdown, the sludge collector removes 45% of the particulate impurities introduced in the feedwater. Total crud removal (blowdown plus sludge trap) increases from 37% to 65% with the addition of the trap. Also, tube deposition is reduced from 52% to 29% with the addition of the trap.

9. Conclusion

The ACR-1000 SGs are larger than the currently operating CANDU steam generators but within the design and operating experience of large replacement PWR steam generators supplied by BWC.

The design of the ACR-1000 SGs utilizes extensive experience gained by BWC from the supply of 289 steam generators for both CANDU plants and US PWR stations. The major design features incorporated into the preliminary ACR-1000 SG design are the integral preheater with a circulation promoting hot leg flow slot, lattice grid tube supports, tightly spaced flat bar U-bend restraint system, high performance moisture separators and a sludge collection system integral with the primary separator deck.

This design meets the AECL technical specification requirements for the performance of the ACR-1000 SGs. BWC continues to review the proposed ACR-1000 steam generator design to provide maximum reliability such that the goal of increased design life can be realized.

8. Table 1: Steam Generator Experience List

CANDU Plants	No. OF STEAM GENERATORS	PWR Plants	No. OF STEAM GENERATORS
NPD	1	MILLSTONE 2	2
KANUPP (Pakistan)	6	McGUIRE 1, 2	8
PICKERING 1-8	96	CATAWBA 1	4
BRUCE 1-8	64	GINNA	2
DARLINGTON 1-4	16	ST. LUCIE 1	2
PT. LEPREAU	4	BRAIDWOOD 1	4
GENTILLY 2	4	BYRON 1	4
EMBALSE (Argentina)	4	D.C. COOK 1	4
CERNAVODA 1, 2 (Romania)	8	CALVERT CLIFFS 1, 2	4
WOLSONG 2, 3, 4 (Korea)	12	OCONEE 1, 2, 3	6
QINSHAN 1, 2 (China)	8	CRYSTAL RIVER 3	2
BRUCE 1, 2, 4 (replacements)	24		
CANDU SGs	247	PWR RSGs	42
TOTAL SGs: 289			

Table 2: Comparison of BWC ACR-1000 design details to CANDU 6, Darlington and System 67 Replacement Steam Generators

	CANDU 6	Darlington	System-67 RSG	ACR-1000
Number of SGs	4	4	2	4
Heat Transfer per SG, MW (th)	516	664	1355	802
S/G heat transfer area, m^2	3195	4830	8705	8454
Steam quality at steam nozzle	99.75	99.75	99.95	99.9
Number of tubes per SG	3530	4663	8523	7234
Tube material	Alloy 800 (modified)	Alloy 800 (modified)	Alloy 690 TT	Alloy 800 (modified)
Tube diameter/wall thickness, mm	15.88/1.13	15.88/1.13	19.05/1.07	17.46/1.07
Tube pitch to tube diameter ratio	1.52	1.54	1.33	1.42
Integral preheater	Yes	Yes	No	Yes
Drum diameter, m	3.8	4.73	6.1	4.65 (max)
Overall height m	19.3	22.2	19.1	<24

Table 3: ACR-1000 SG Tube Bundle Sizing Requirements

Parameter	Units	Design Value
Heat Transfer per SG	MW_t	802.2
Primary flow rates per SG	kg/s (lb/hr)	3264 (25.905 x 10^6)
Primary inlet temperature	°C (°F)	318.57 (605.43)
Primary inlet pressure	MPa (psia)	11.1 (1609.9)
Steam pressure	MPa (psia)	6.0 (870.0)
Feedwater temperature	°C (°F)	217 (423)
Blowdown flow rate	%	1.0% of steam flow
Tube Plugging (margin included in fouling resistance)	%	0%
Fouling Resistance	m^2 °C/kW (ft^2°F hr/Btu)	.02642 (.000150)
Tube Material		Alloy 800 (modified)
Tube size (O.D.)	mm (in)	17.46 (11/16)
Tube wall thickness	mm (in)	1.07 (0.042)

Table 4: Babcock & Wilcox Start-Up Moisture Carryover Test Results

Station	Separator Type	MCO Measured
Millstone 2	CAP 2	0.022%
Ginna	CAP 3	0.015%
Catawba	CAP 3	0.046%
McGuire 1	CAP 3	0.052%
McGuire 2	CAP 3	0.047%
St. Lucie 1	CAP 2	0.011%
Byron 1	CAP 3	0.077%
Braidwood 1	CAP 3	0.045%
Wolsong 4	CAP2	0.027%

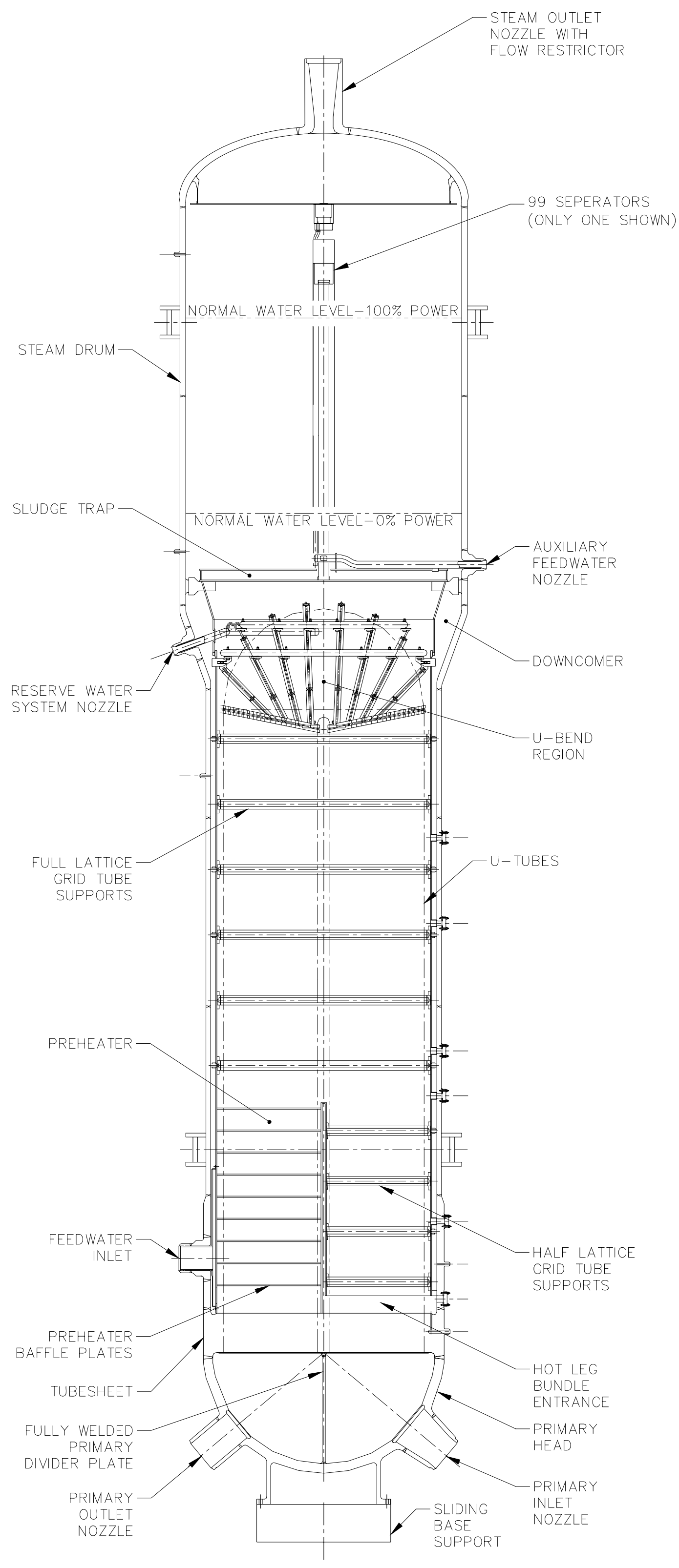

Figure 1 – Overall Arrangement of the ACR-1000 Steam Generator

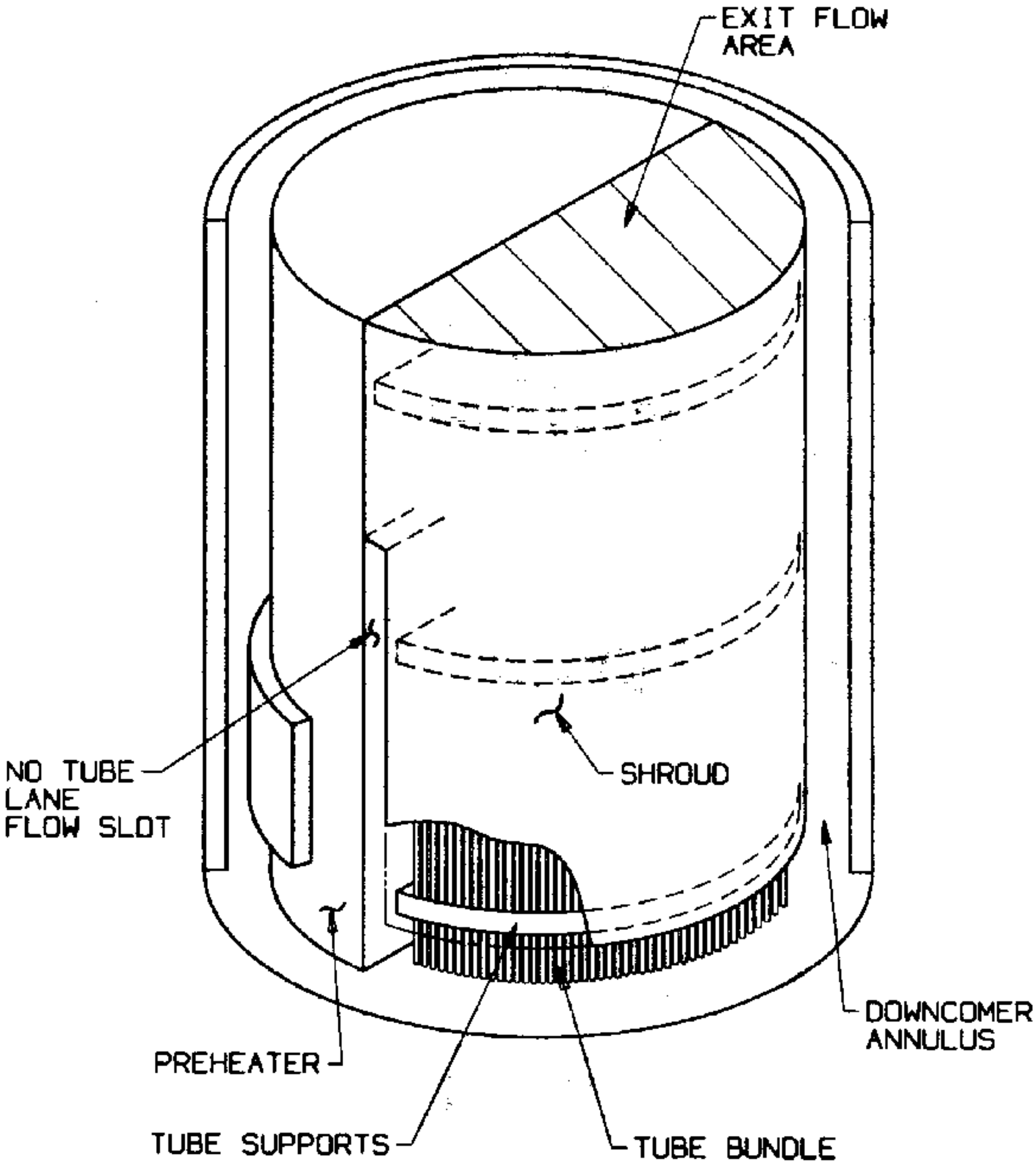

Figure 2 – Isometric View of Preheater

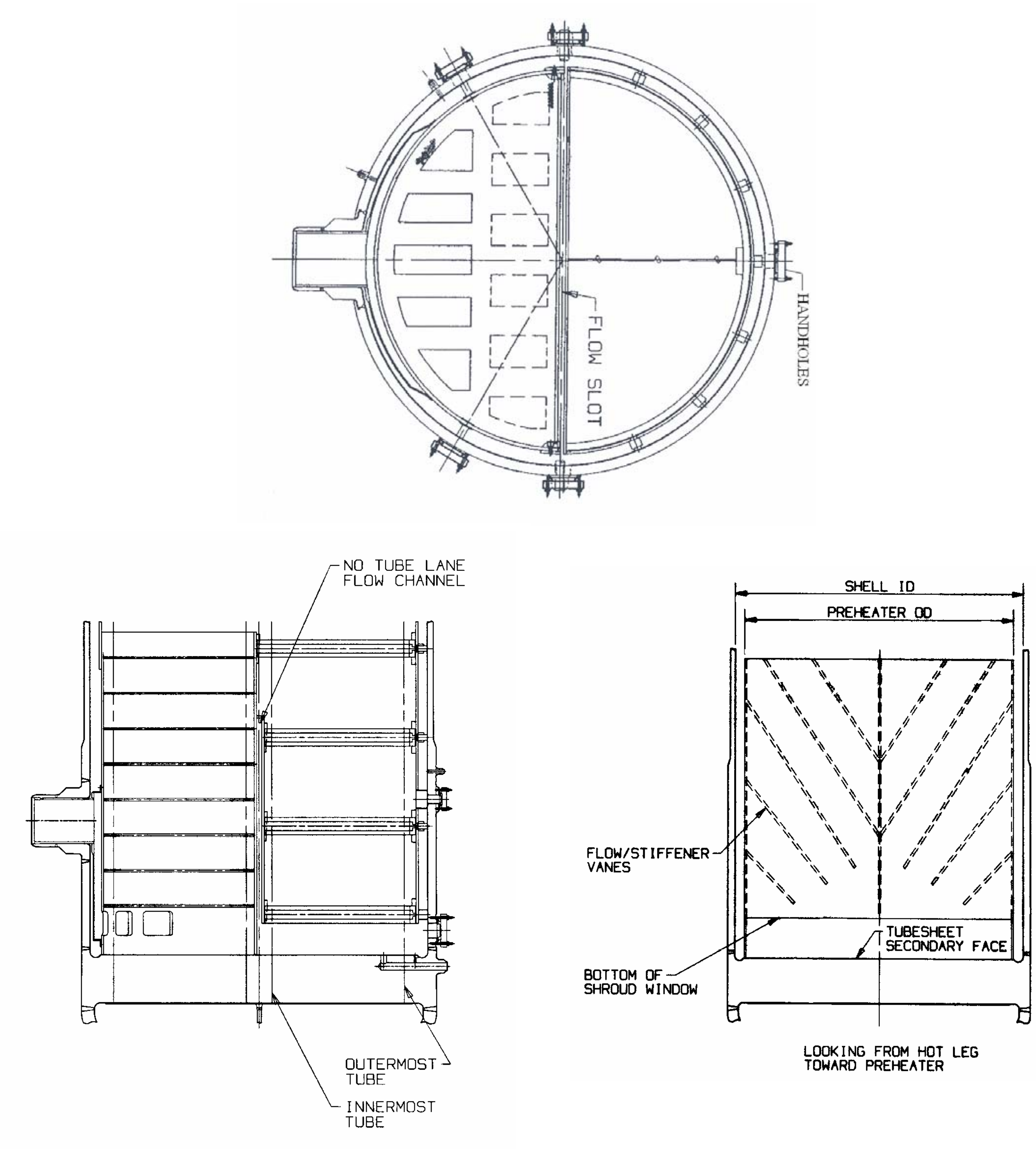

Figure 3 – ACR-1000 Preheater Arrangement

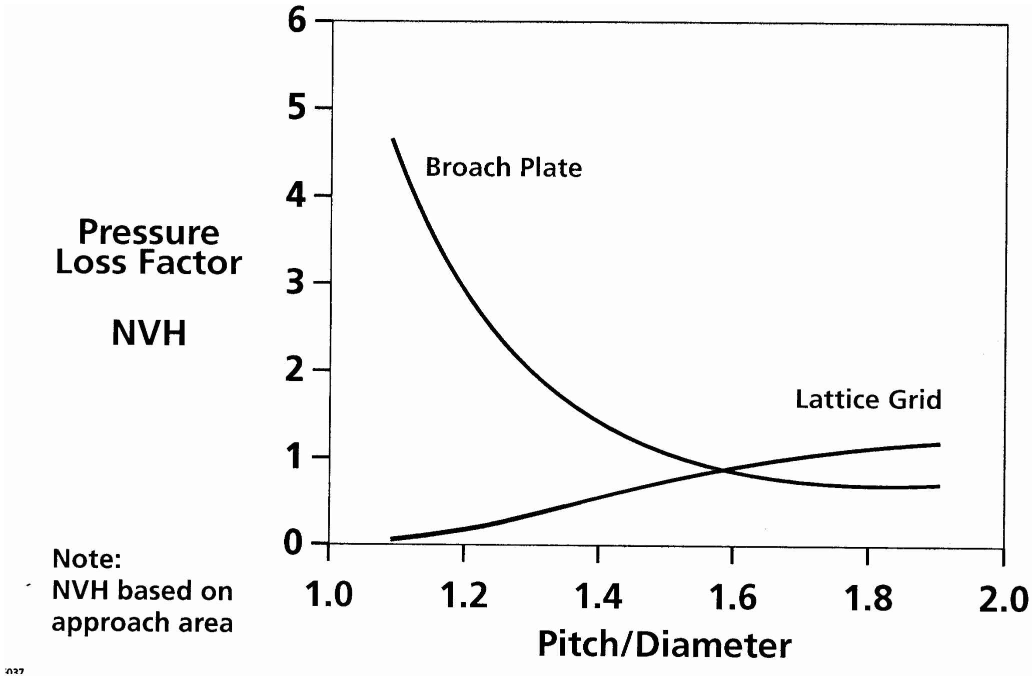

Figure 4 – Tube Support NVH versus Pitch / Diameter Ratio

Figure 5 – Details of BWC Lattice Grid Tube Support

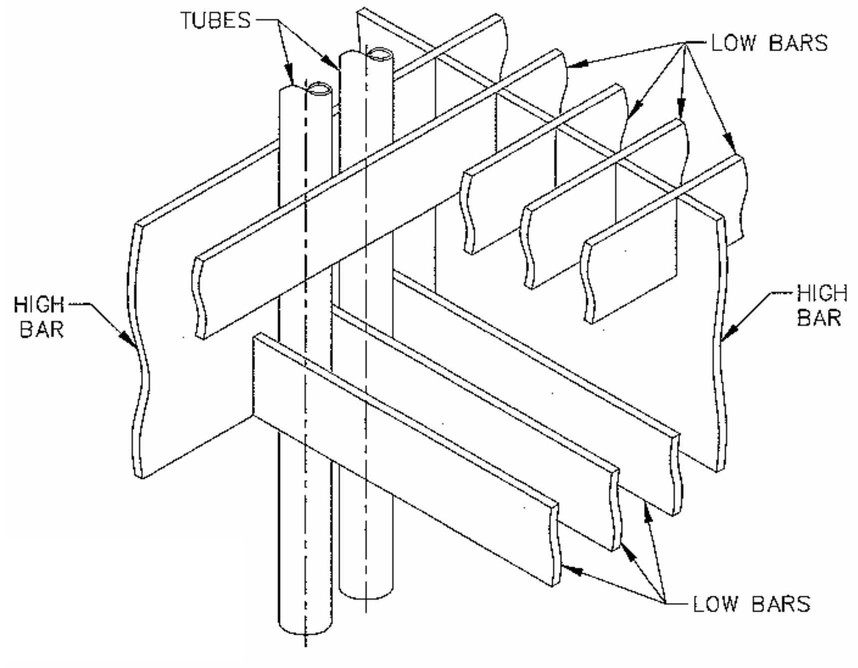

Figure 6 –Lattice Bar Tube Support Arrangement

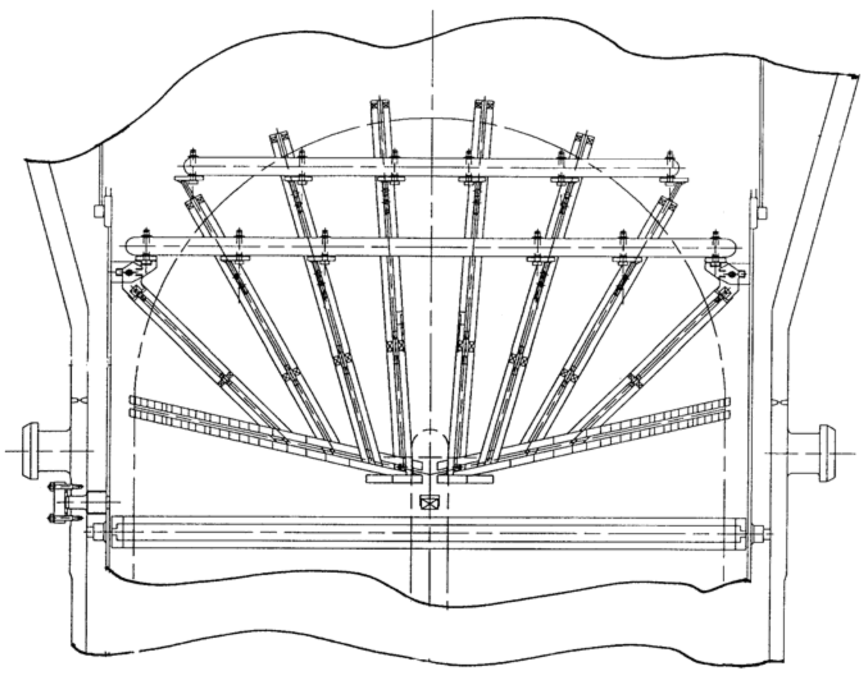

Figure 7 – Flatbar U-Bend Restraint Configuration

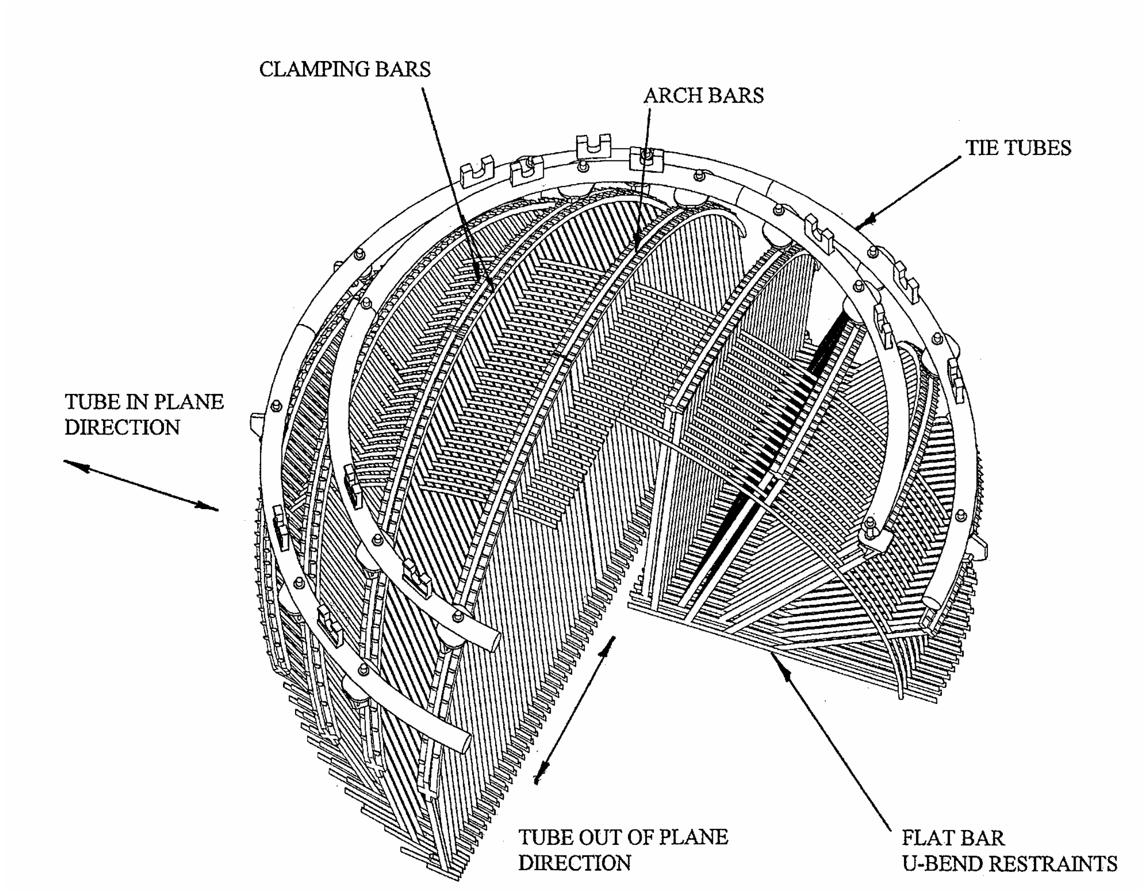

Figure 8 – Flatbar U-Bend Restraint Arrangement

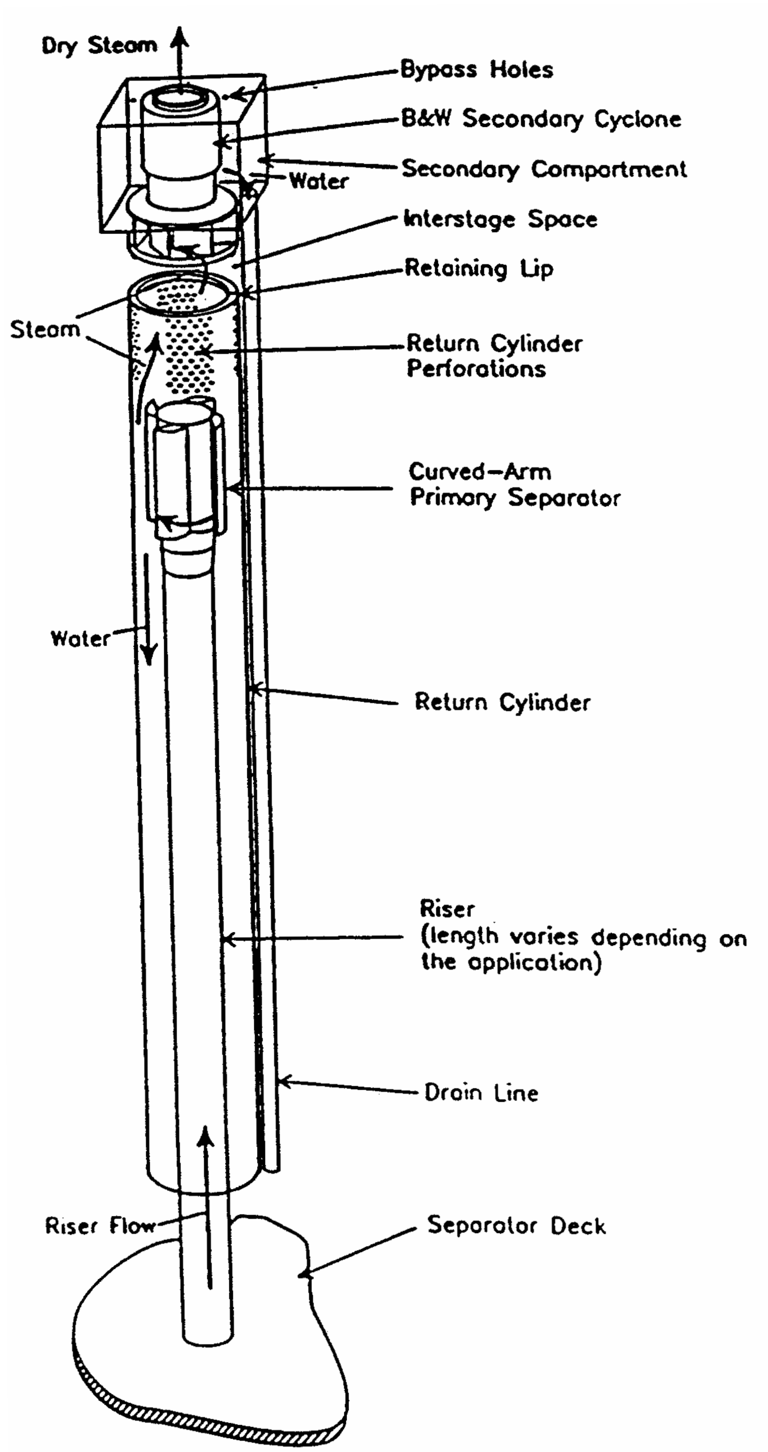

Figure 9 – Primary and Secondary Steam Separators

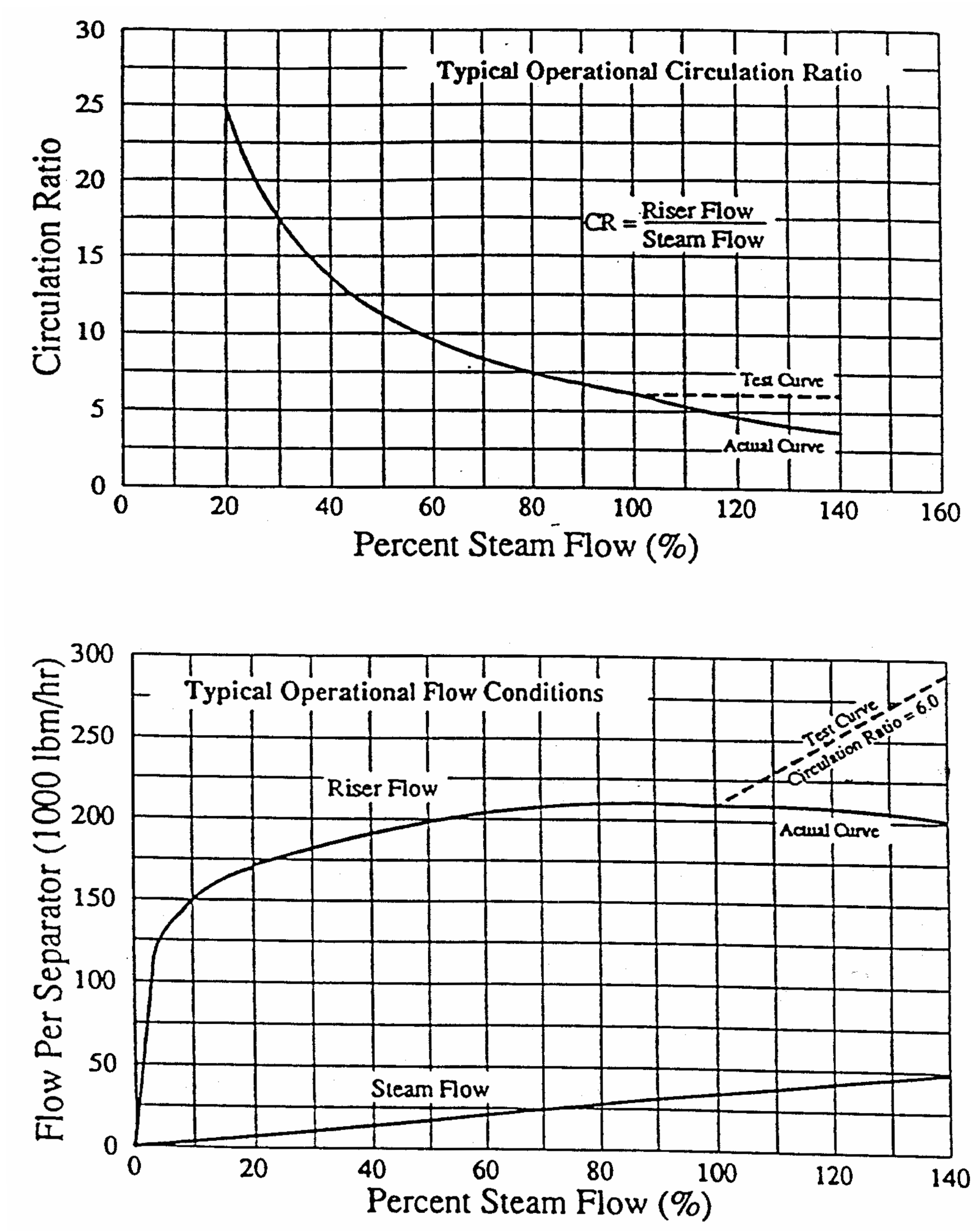

Figure 10 – Typical Operational Circulation Ratio and Flow Conditions

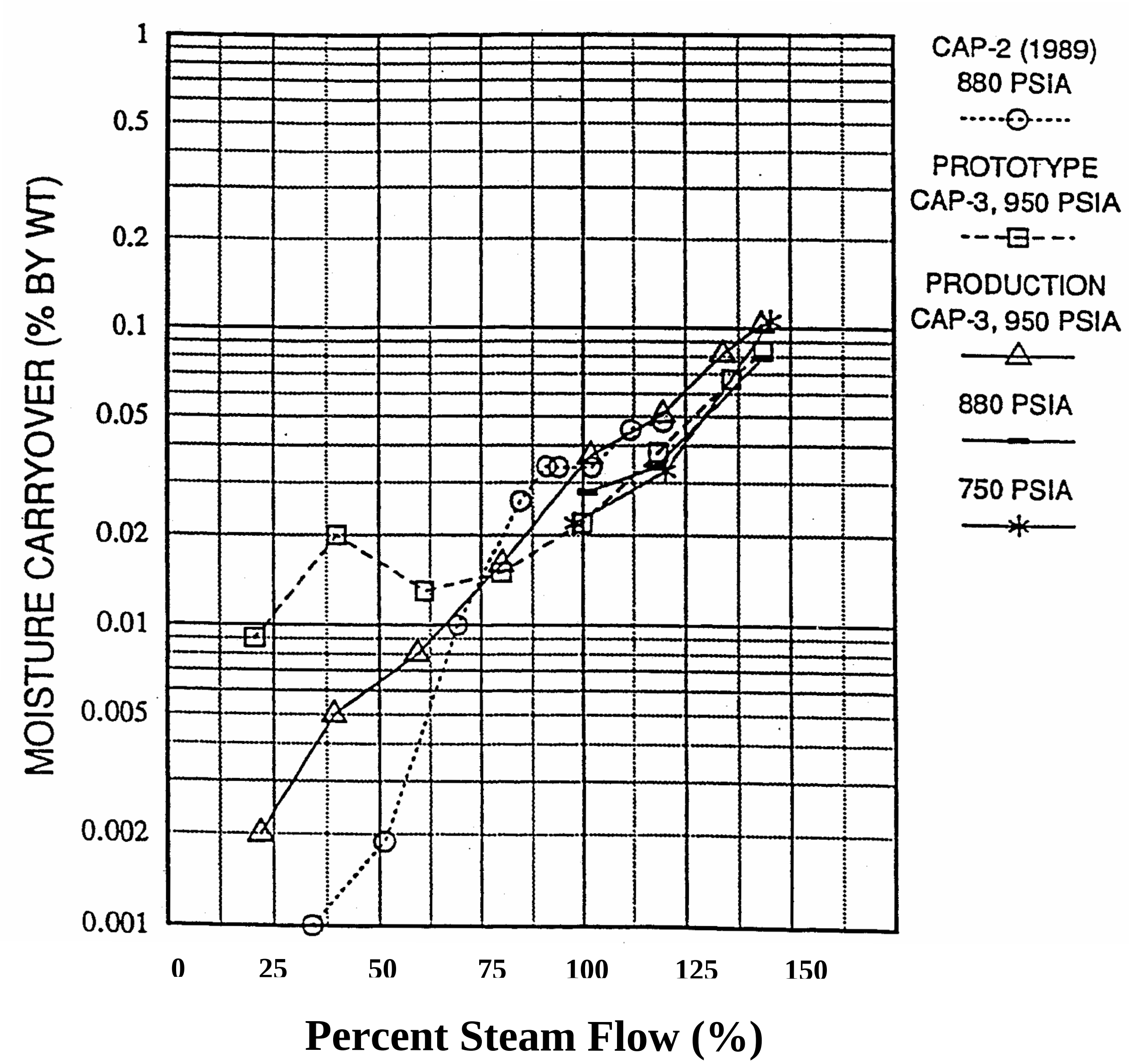

Figure 11 – Moisture Carryover for Power Series Testing

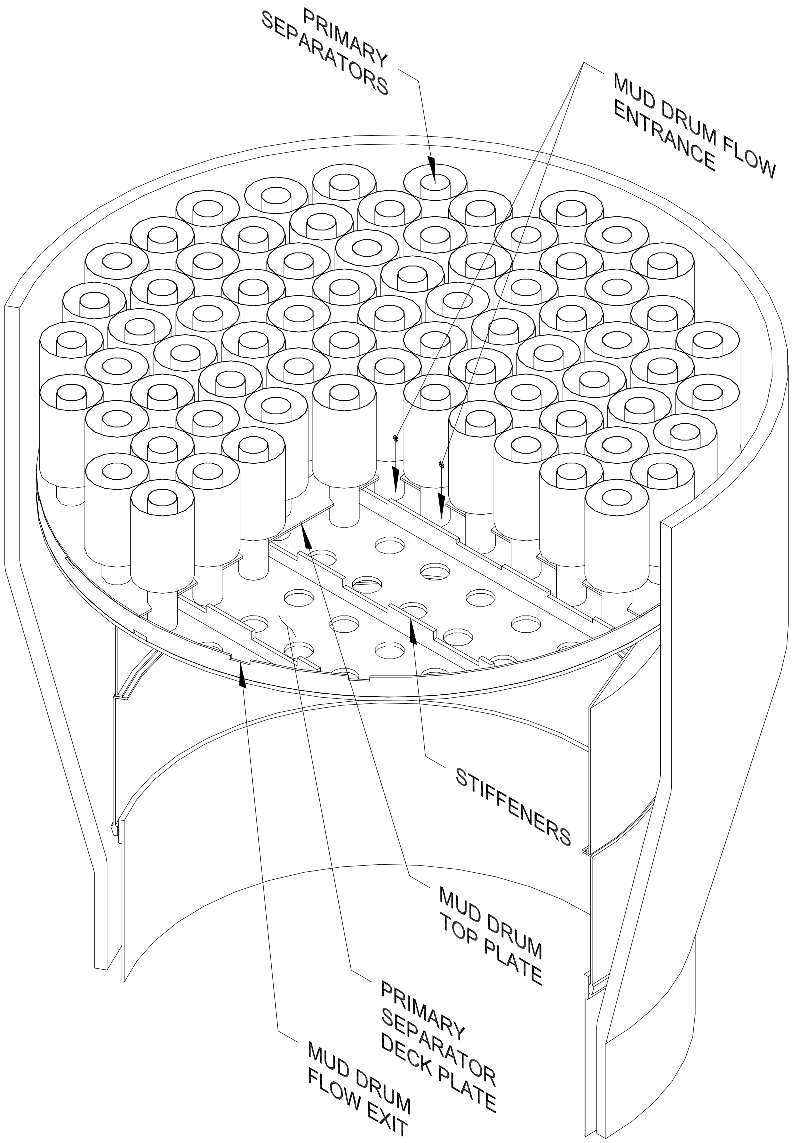

Figure 12 – Sludge Collector Arrangement

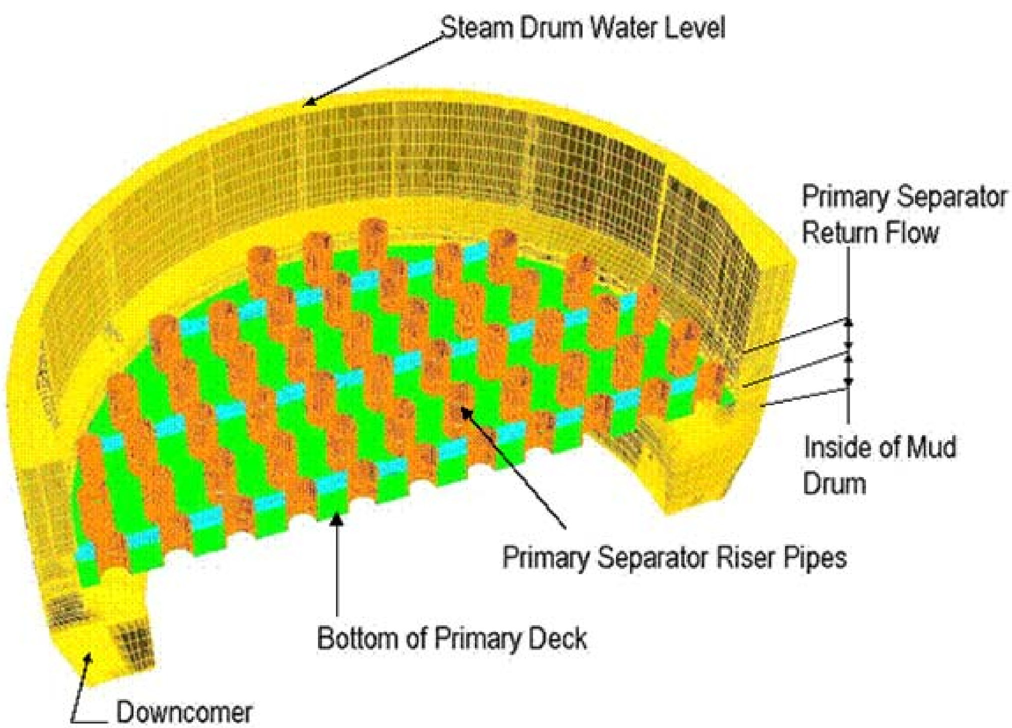

Figure 13 – CFD Model Solution Domain

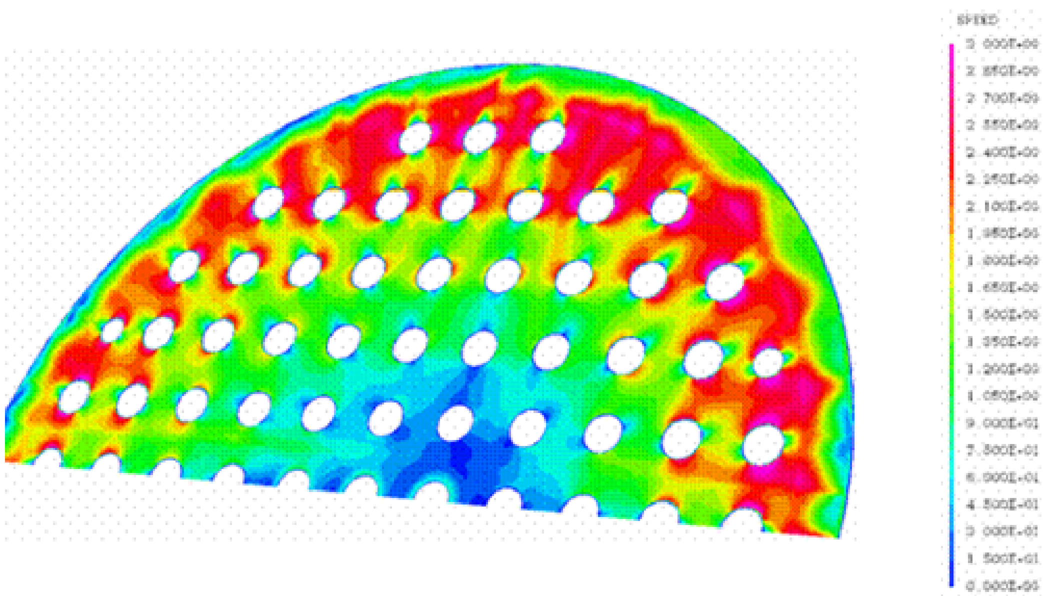

Figure 14 – Velocity Profile Above Primary Separator Deck Without Sludge Collector

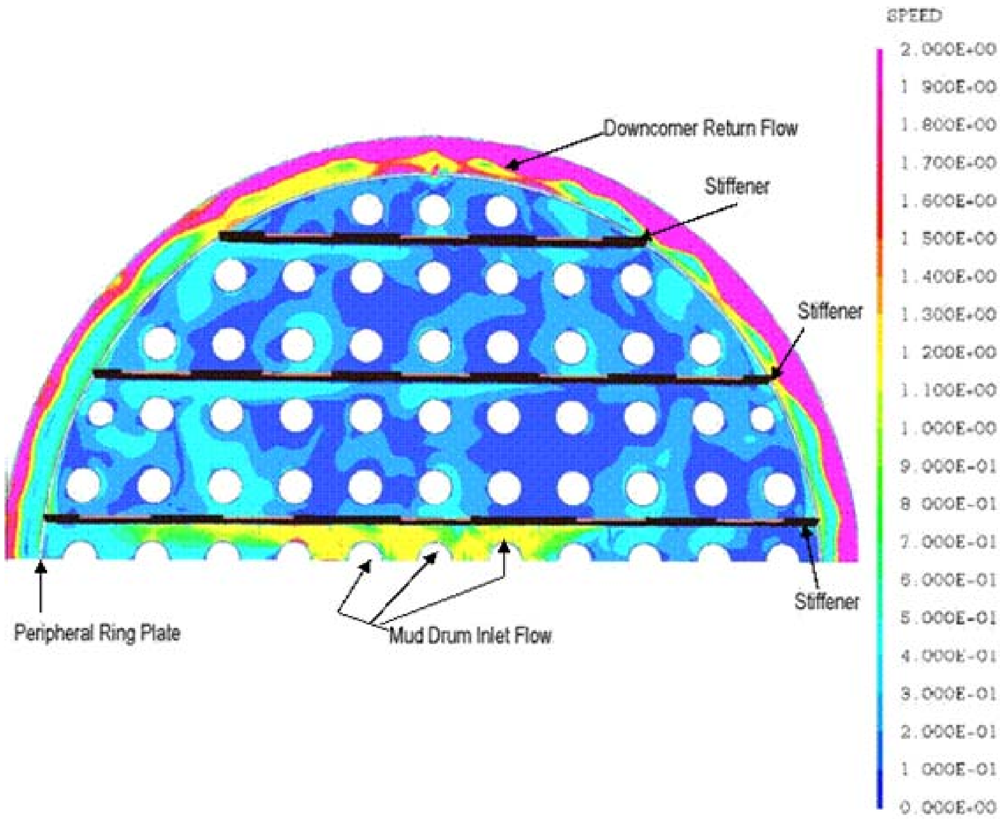

Figure 15 – Velocity Distribution within the Sludge Collector

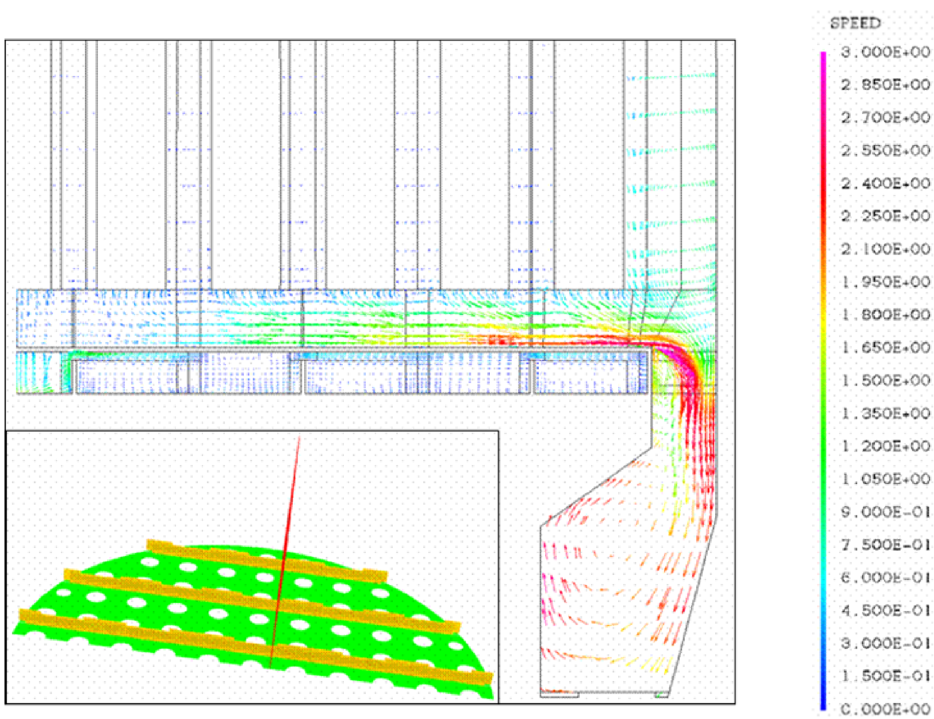

Figure 16 – Sludge Collector Velocity Profile