STEAM GENERATOR DESIGN REQUIREMENTS FOR ACR-1000

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1. Introduction

Atomic Energy of Canada Limited (AECL) has developed the ACR-1000 * (Advanced CANDU Reactor-1000) to meet market expectations for enhanced safety of plant operation, high capacity factor, low operating cost, increased operating life, simple component replacement, reduced capital cost, and shorter construction schedule.

The ACR-1000 design is based on the use of horizontal fuel channels surrounded by a heavy water moderator, the same feature as in all CANDU® ** reactors. The major innovation in the ACR-1000 is the use of low enriched uranium fuel, and light water as the coolant, which circulates in the fuel channels. This results in a compact reactor core design and a reduction of heavy water inventory, both contributing to a significant decrease in capital cost per MWe produced.

The 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 plant design is adaptable to a single unit configuration, if required. This paper focuses on the technical considerations that went into developing some of the important design requirements for the steam generators for the ACR-1000 plant and how these requirements are specified in the Technical Specification, which is the governing document for the steam generator (SG) detail design. Layout of these SGs in the plant is briefly described and their impacts on the SG design.

2. Process design requirements for steam generators

The increased reactivity of the low enriched fuel allows more flexibility in the design of key reactor core components in the ACR design, including increased thickness of pressure tubes. Thicker pressure tubes allow for a higher coolant pressure and temperature, which in turn allow higher steam (turbine) pressure and temperature. A higher thermal efficiency of the turbine cycle is thus achieved compared to the currently operating CANDU plants, which operate with a lower steam pressure.

2.1 Selection of Operating parameters for steam generator design

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* ACR-1000™ (Advanced CANDU Reactor™) is a trademark of Atomic Energy Canada Limited (AECL).

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To achieve improved safety margins for the reactor, the Heat Transport System (HTS) coolant at the outlet of the reactor is kept subcooled by about 1 C throughout the design life of the station. The HTS coolant flow rate is determined by the maximum channel flow rate achievable through considerations of fuel bundle vibration, pressure tube fretting and the Flow accelerated corrosion (FAC) of the carbon steel components of the HTS. Whereas increasing the channel flow rates provide increased safety margins, these considerations limit the flow rate.

For a given channel flow rate, HTS pressure and temperature, the maximum channel power is determined by the safety margin to fuel cooling. The higher the channel power, the lower the safety margin, but the higher power has the benefit of reducing the number of channels needed and can be shown to be economically cost effective up to a certain point.

Based on the above considerations, and the design of feeders (which must be consistent with the required lattice pitch of the fuel channels to achieve negative void reactivity in the core), a range of HTS coolant and SG steam conditions to the turbine was developed. This range (as given in Table 1) was then used to assess the impact of each parameter on safety margin and cost of the HTS design and to choose an optimized design option.

The HTS performance assessment was done using NUCIRC, a steady state thermal-hydraulic code developed by AECL. The code can be used to predict channel flow, pressure, temperature, and quality at any location in the HTS, to determine critical channel power (i.e. channel power at dryout), and to size HTS equipment including the HT pumps, steam generators and feeders.

In parallel, an assessment of the Balance of Plant (BOP) thermal cycle efficiency, turbine performance and net electrical output for varying steam conditions at the turbine, was conducted. Higher steam temperatures result in higher cycle efficiency but a larger SG would be required due to reduced temperature difference between the heat transport coolant and the steam produced in the steam generator.

The results of the above optimization studies are given in Table 1, which shows the final design parameters selected including the conditions for the ACR-1000 steam generator. A comparison of these conditions with CANDU 6 SG is also given.

2.2 Steam generator sizing

Only vertical Recirculating Steam Generators (RSGs) with and without integral preheaters were considered based on considerations of space and proven operational experience. A typical CANDU SG is shown in Figure 1. The heat transport light water coolant which carries the heat from the reactor flows through the inverted U-tubes and the heat is transferred to the naturally recirculating light water on the outside of the tubes, to produce steam. For pressure tube reactors, the limitation in the allowable individual channel flow rate per kW heat removed, results in a steeper reactor inlet- to-outlet temperature difference compared with the PWR reactors. The reactor inlet temperature limits the maximum steam temperature achievable in the steam generator unless a preheater is used to raise the temperature at which steam is produced. This is shown in Figure 2, which shows how the "pinch point" governing the heat transfer area is moved from SG outlet to the top of the integral preheater. Introducing quality in the coolant allows a somewhat higher steam temperature (as in CANDU 6) but from safety considerations, it was decided to keep the coolant sub-cooled as mentioned earlier.

Two options were considered for the number of steam generators needed to transfer the heat from the reactor: 2 larger or 4 smaller steam generators. An evaluation was done considering the following issues: design and manufacturing capability; acceptability of secondary side thermal-hydraulics in such large SGs (see Table 2 for comparison to other CANDU SGs) with integral preheaters, particularly with respect to the rate of material deposition on tubes due to expected lower recirculation ratios, other system-related considerations; and cost of each option.

For the assessment of the two options, preliminary sizing of the steam generator was carried out using NUCIRC. AECL also requested B&W, who have supplied steam generators for CANDU plants in the past, to help size the SGs for the two options, using their in-house code CIRC. A third code, THIRST which is a 3-D thermal hydraulic code developed by AECL, was used to predict the secondary side thermal hydraulics in detail to understand local effects of velocity/pressure/temperature/two-phase quality on the SG performance.

The assessment concluded that the 4-SG option was the preferred option from equipment and HTS system performance considerations and allows the adoption of the two figure-of -eight loops for the HTS as shown in Figure 3, which is a proven configuration for CANDU operating plants.

Following the assessment, further refinements to the steam generator operating conditions were required for the 4-SG option, as the HTS design progressed. This included reducing both the primary and secondary operating pressures by one MPa and using subcooled heat transport coolant instead of coolant with some quality in it. B&W have continued supporting AECL in refining the steam generator size to match the specified operating parameters. Their contribution to the ACR steam generator design is presented separately. The final design parameters are as shown in Table 1. Preliminary design details of the steam generators based on these final parameters are given in Table 2**,** in comparison to other CANDU SGs.

3. Station layout requirements for steam generators

The ACR-1000 heat transport system arrangement within the reactor building is shown in Figure 4. As mentioned earlier, the arrangement is based on the successful and internationally recognized CANDU 6's "figure-of-eight" loop (Figure 3). There are four steam generators and four heat transport pumps arranged in two loops, with the reactor core in the centre. This configuration allows for on power refueling which is a unique design feature for CANDU reactors.

As shown in Figure 4, the vertical, recirculating SGs, the heat transport pumps and the reactor headers are located above the reactor; this permits the heat transport coolant to be drained to the header elevation for maintenance of the pumps and steam generators and also facilitates natural circulation of the coolant when the pumps are unavailable.

The steam generators are located and supported on concrete structures, which transmit their weight to the base slab of the reactor. The lateral restraints are designed taking into consideration the seismic and burst pipe loads.

The ACR standard product design allows a planned replacement of steam generators, if necessary. The replacement scheme envisaged requires holes to be cut into the containment dome above each of the steam generators. The steam generators will be lifted and removed through the holes and the replacement steam generators installed through the same holes using a very heavy lift crane.

4. Technical Specification requirements for SG design

AECL, as plant designers, perform preliminary sizing of equipment where feasible, but do not undertake detailed design of equipment. AECL develop the design requirements for the detailed design of equipment, which they procure from reputable equipment suppliers in private industries. The Technical Specification for the steam generator is the primary document that captures the design requirements to be met by the equipment supplier. It specifies requirements pertaining to performance, safety, pressure and level control, ability to withstand operating, seismic and accident loads, fabrication, inspection and testing, reliability, maintainability, quality assurance, documentation, marking and identification and preparation for shipment. The following sections will discuss some of these requirements for design features that would contribute to improved reliability and maintainability of the SG and the technical considerations that led to these requirements based on operational experience and R&D programs.

4.1 Improved Reliability

The performance reliability of CANDU 6 steam generators has been excellent to date, contributing to plant capacity factors in excess of 90%. The ACR 1000 design seeks to further improve upon this record by requiring some of the proven design features to be retained and requiring additional design features that would contribute to increased reliability. Some of these requirements and their basis are discussed below:

a) Tubing

CANDU 6 steam generators use modified alloy 800 (SB-163 UNS N08800) as tubing material and this will continue to be AECL's material of choice for ACR-1000. Starting with the Cernavoda 1 plant in Romania, mill annealed, "as received" (i.e.straightened and ground) U-Bent tubing has been used in all CANDU steam generators and the operational experience with this material has been very good. While its corrosion resistance, particularly to SCC, at the operating temperatures and water chemistries of CANDU SGs is known to be excellent, it has been decided, given the extension of service life to 60 years, to improve on the corrosion resistance by reducing the residual tensile stresses in the bent tubing. Various methods for stress relief are under consideration at the time of writing this paper.

A competing tube material to alloy 800 is the thermally treated alloy 690 used in many of the replacement SGs for PWRs in the US. This material is considered equivalent to alloy 800 in terms of corrosion resistance at the ACR operating temperatures and water chemistry conditions. Customer preference can influence the material selected for a given plant.

b) Secondary side design

Materials

As a nuclear Class 1 component, the pressure boundary and the external SG support materials must meet the requirements of the ASME Section III Code. Forgings are required for the shell and the drum to minimize welds for inspection.

All carbon steel and low alloy steel pressure retaining material , which have wetted surfaces in service shall have 0.3% minimum chromium content to minimize FAC.

The TS specifies materials for significant internals that may be prone to FAC. The feedwater nozzle thermal sleeve, the preheater feedwater box and its internals, baffles and impingement devices are required to be stainless steel. Tube supports in the boiling zone and any component in contact with the tubing are required to be 410S stainless steel or equivalent. This material is specified due to its excellent corrosion resistance and its compatibility with the alloy 800 tubing material for good fretting wear performance. It also allows more accurate inspections of tubes and tube-to-support clearances as compared to non-magnetic materials such as austenitic stainless steel. The material for steam separating equipment is required to be austenitic stainless steel.

Materials for all other internals shall be selected by the Supplier of SG but are subject to review and acceptance by the purchaser.

Recirculation ratio

CANDU steam generators have always been designed with a high recirculation ratio (approximately 5:1) on the secondary side. High recirculation ratios result in high flow velocities and low steam qualities across the tube sheet and in the tube bundle. This would in turn, reduce the deposition rate of fouling matter on tubesheet and the tubes. The recirculation ratio has an inverse relationship to the average steam quality in the tube bundle and experiments have shown that above steam qualities of about 40 %, the rate of deposition of fouling increases at a very rapid rate. Another benefit of a high recirculation ratio is the reduction of concentration of chemicals hiding out in crevices due to reduced steam qualities. Since chemicals stay preferentially in water in two-phase flow, high steam qualities promote higher concentration of chemicals in the water phase and higher concentrations in crevices. Yet another benefit is the reduction of potential for flow instability associated with high steam qualities.

Based on the above considerations, and keeping in mind that other design features (such as tube pitch to diameter ratio, tube support plate design, U Bend support design) also influence steam qualities in the tube bundle, the requirement in the technical specification has been modified. The current requirement is for the supplier to show that the design is capable of achieving as high a recirculation ratio as possible <u>and</u> limits the maximum steam quality anywhere in the tube bundle to 40% under all operating conditions.

<u>Fouling margin</u>

The fouling margin for SG design is based on thermal performance trends to date at CANDU 6 plants, taking account of the design differences between the CANDU 6 plants and ACR. The fouling margin includes contributions from fouling on the primary and secondary sides of the tube bundle and some allowance for loss of heat transfer area caused by tube plugging. The recoverable component is that due to tube bundle fouling since it can be removed by removing the deposit, hence it is not life limiting. The contribution to the fouling margin by tube plugging (and removal of SG tubes) is not recoverable.

Primary side fouling is caused by precipitation of magnetite inside the tubes as the HTS fluid is cooled during its passage through the SG. The source of the iron is flow-accelerated corrosion of the carbon steel feeders in CANDU 6. For ACR-1000, the material of choice for the feeders and headers will be stainless steel. Taking into account other factors such as higher temperatures, a significant reduction is envisaged in the buildup of deposits on the primary side due to FAC.

Secondary side fouling is caused by deposition of material carried into the SG in the feed water. The experience with PWR SGs is that secondary side fouling enhances the heat transfer for the first few years of operation. When the average fouling deposit thickness exceeded 50 micrometers corresponding to a deposit loading of about 0.2 kg /m^2, plants started to experience performance degradation. So, the recommendation is to a) design to minimize the fouling rate and b) to perform steam generator cleaning when the deposit loading reached about half the above value. Based on this, contribution of secondary side fouling to the fouling margin has been discounted.

The above considerations led to the specification of a design fouling margin for the steam generator of 0.0000264 m^2.C/W (0.00015 hr.ft^2.F/Btu), which is somewhat lower than CANDU 6, but still quite conservative in keeping with the required design life of the station.

Blow down design

Crud transported to the SG with the feedwater either deposits (fouling) or remains in suspension where it can be removed by blow down. Blow down efficiency is defined as the rate of removal of material from the SG by blow down divided by the rate of transport of material into the SG with the feedwater. Since blow down only removes particles that are already in suspension, blow down efficiency will depend primarily on the SG fouling rate and on the blow down rate. There is an economic incentive for removal of crud while still in suspension, since once deposited on tubing, removal of these deposits can only be done with a costly cleaning process.

Studies have shown that blow down efficiency increases with increasing blow down rate and with decreasing SG fouling rate. By increasing the continuous blow down rate to 1% from 0.1% used in CANDU 6 SGs, the blow down efficiency can be increased from 10% to 60%. Blow down rate of 1% should remove more than 50% of the crud coming into the SG. AECL is currently considering using alternate water treatment chemistry in place of morpholine chemistry in the steam cycle, which results in a 5-time reduction in fouling rate. Combining this with increased blow down could result in the majority of crud coming into the SG being removed by blow down.

Increasing the blow down rate requires recovery of the blow down water and as much of the heat energy in it as possible, from an economic viewpoint.

For ACR-1000 SG, the specification requirement is to have a continuous blow down rate of 1% and for the heat energy in the blow down flow to be recovered and the flow recycled. The provisions for blow down in the SG should be simple and conducive to capturing the crud particles as directly as possible (i.e. without requiring change of direction of the fluid streamlines). The recycled blow down flow will also reduce the emission to environment.

Sludge trap

The purpose of a sludge trap is to provide a benign region for collecting crud in the SG where it can be easily removed and where it can cause no degradation to either operation or to components of the SG. An example would be the primary separator deck where there is no heat transfer to consolidate sludge which should remain soft and hence amenable to easy removal.

The requirement is for providing such a sludge trap that processes a small fraction of the saturated water from the separators and reduces the amount of deposits that builds up on the tube bundle.

Corrosion allowances

Corrosion allowances are conservatively calculated and specified in the technical specification for materials based on past practices, operational experience to date and the advice of chemical cleaning experts at AECL. The allowances include contributions from general corrosion, corrosion resulting from chemical cleaning and flow accelerated corrosion (FAC). These allowances also take into account the material selected for a given subcomponent e.g. plain carbon steel, steel with 0.3% chromium and stainless steel or high nickel alloy. The allowances are also based on water lancing the secondary side at specified intervals to keep the tubes and tubesheet clean to minimize localized corrosion (e.g. pitting).

Flow- Induced Vibration (FIV).

Designing for preventing FIV damage of the tube bundle is a requirement. AECL has accumulated an extensive knowledge base on FlV and fretting wear technologies from R&D programs that date back to the early ‘70s and is considered a world leader in this area. A stand-alone FIV specification for steam generators and liquid heat exchangers is in place that provides analysis methods, requirements and criteria aimed at preventing tube failures due to fretting-wear associated with FIV. The SG supplier is required to show how his design meets these requirements through documented analysis. The FIV specification is kept updated periodically to reflect new knowledge.

Tube-to-tubesheet joint

Hydraulic expansion spanning the full depth of the tubesheet is the current standard for the tube-to-tubesheet joint. It is considered to be the optimum crevice closure method currently available to minimize the potential for crevice corrosion within the tubesheet.

c) Primary side design

On the primary side, two manways will be required, one in the inlet and one in the outlet plenum. The divider plate will be required to be fully welded at its periphery to the tubesheet and the primary head, to ensure zero leakage from plenum to plenum. The divider plate design will require full and unimpeded access for inspection and cleaning of all tubes. An external manipulator such as the one shown on Figure 5 is a requirement for removal and replacement of primary manway covers, but alternate suggestions from suppliers will be considered for this operation depending on the design of the covers.

4.2 Improved inspection and maintenance

It is recognized from worldwide experience with operation of Recirculating SGs that regular inspection and maintenance of the SGs are fundamental for tube survival. Water lancing and chemical cleaning are well known methods for removal of sludge on the secondary side of SGs. In addition, primary side cleaning technologies such as mechanical cleaning of magnetite deposits using steel shots and CANDECON are also currently available. However, for ACR 1000 SGs, these remediation strategies may not be required given the limited carbon steel surface area in the heat transport system.

Use of these methods requires provision of openings such as manways and hand holes on the primary and secondary side of the SG for inspection and cleaning. While provision of such openings has been a specification requirement for recent CANDU 6 SGs, for ACR-1000, which is a much larger SG, the number and size of some of these openings and the method of providing leak-tight closure to these openings while in service, will be decided in consultation with maintenance experts at AECL and with the SG supplier.

Nozzle dams for primary nozzles capable of quick installation and removal are required during maintenance in the primary head. These dams are required to be capable of withstanding a pressure differential of about 100 kPa (35 ft of water) without leaking.

Accessibility to SG for maintenance

To inspect and clean the tube bundle and internals effectively during maintenance outages, it is important to include good provisions for accessibility to the SG in the station layout. At the time of preparation of this paper, AECL staff involved in the station layout are working closely with private consultants specializing in equipment maintenance and operation, to optimize the access provisions for equipment including the steam generators.

5. Conclusions

The ACR-1000 SGs are larger than the currently operating CANDU steam generators (but within the size range of the 1000MWe class PWR SGs) and form an important part of the next generation, advanced CANDU reactor, the ACR-1000 nuclear plant. Their design, operation and maintenance are central to achieving the 60-year design life of the station with capacity factors targeted in excess of 90%. In preparing the Technical Specification for these important components, careful consideration was given to retaining as much of the proven technology as possible in their design, consistent with the higher pressures and temperatures of the Heat Transport System in which they function. New requirements based on extensive operational experience and R&D programs have been added for improved reliability and maintainability. Coupled with improvements in water chemistry specifications, and a balance-of-plant design that strives to minimize crud ingress into the steam generators, there is a high level of confidence in achieving the above station targets.

Table 1: Range of ACR-1000 CANDU HTS and BOP Operating Conditions

Design Parameters	CANDU 6 (for comparison)	Range for ACR-1000	ACR-1000
Nominal Max Channel Power, MW	6.5	5.7-7.45	6.6
Number of fuel channels	380	480-580	520
Total Heat Transferred to SG, MW	2064	3192-3508	3208
Gross Electrical Output	728	--	1165
Max. Channel Flow , kg.s Total Core Flow, kg/s	28 8000	22-29 11600-13456	28 13100
ROH Pressure, MPa (a) Temperature, C Quality, % at ROH	10 310 4	11.2-12.2 316-326 0-2.5	11.2 319 1 C subcooled
RIH Pressure, MPa (a) Temperature, C	11.2 266	12.6-13.6 274-284	12.6 275
Steam Pressure, MPa (a) Temperature, C	4.7 260	5.5-7.0 270-286	6.0 275.5
Feedwater Temperature, C	187	--	217

Table 2: Comparison of ACR-1000 preliminary design details to CANDU 6 and Darlington

	CANDU 6	**Darlington**	**ACR-1000**
Number of SGs	4	4	4
Heat Transfer per SG, MW (th)	516	664	802
Steam temperature, C	260	265	275.5
S/G heat transfer area, m^2	3195	4830	8454
Steam quality at steam nozzle	99.75	99.75	99.9
Number of tubes per SG	3530	4663	7234
Tube material	Alloy 800 (modified)	Alloy 800 (modified)	Alloy 800 (modified)
Tube diameter/wall thickness,mm	15.88/1.13	16/1.13	17.46/1.07
Tube pitch to tube diameter ratio	1.52	1.54	1.42
Integral preheater	Yes	Yes	Yes
Drum diameter,m	3.8	4.73	4.65 (max)
Shell diameter,m	2670	3048	3810
Overall height,m	19.3	22.3	<24

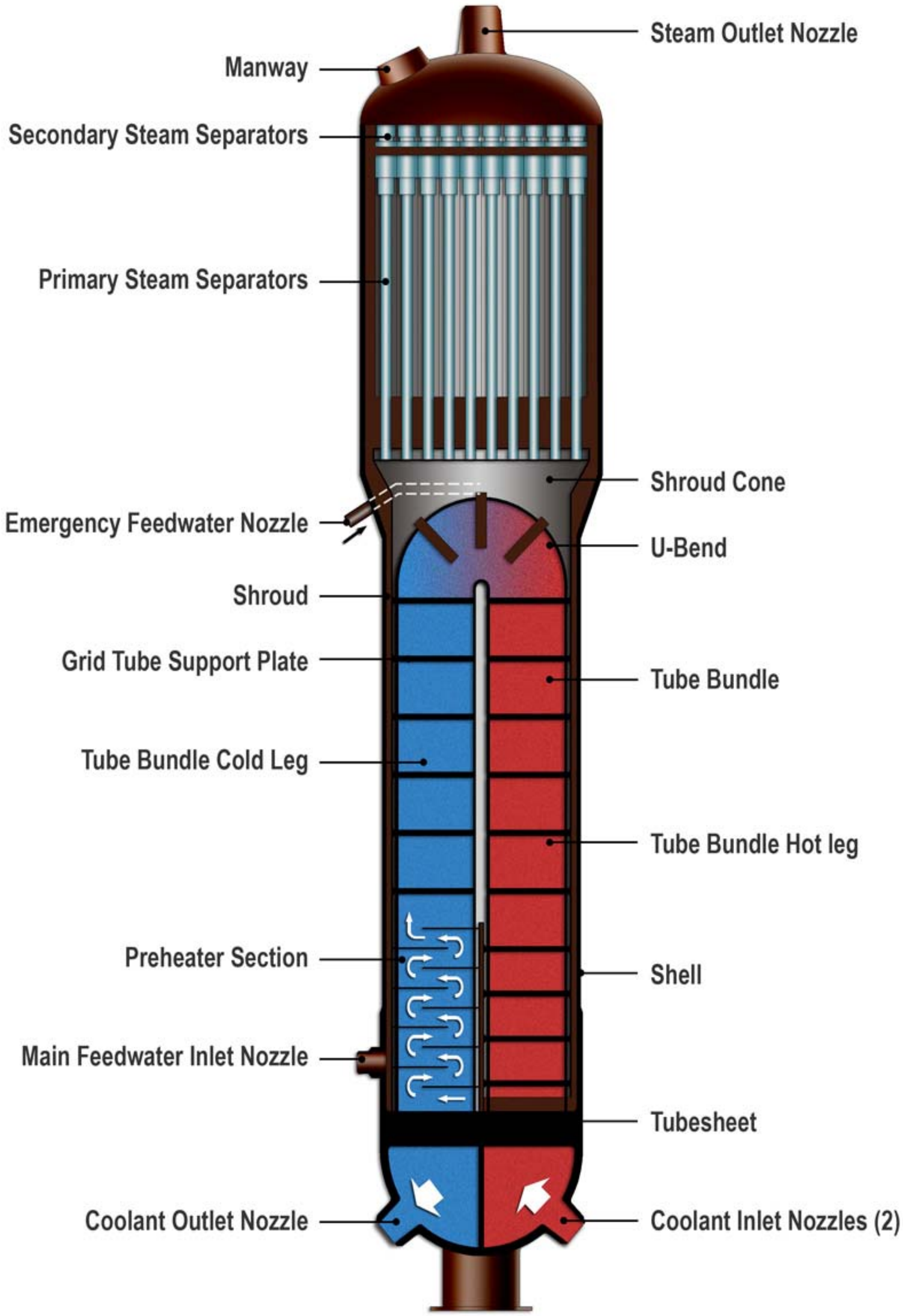

Figure 1: A typical CANDU Steam generator

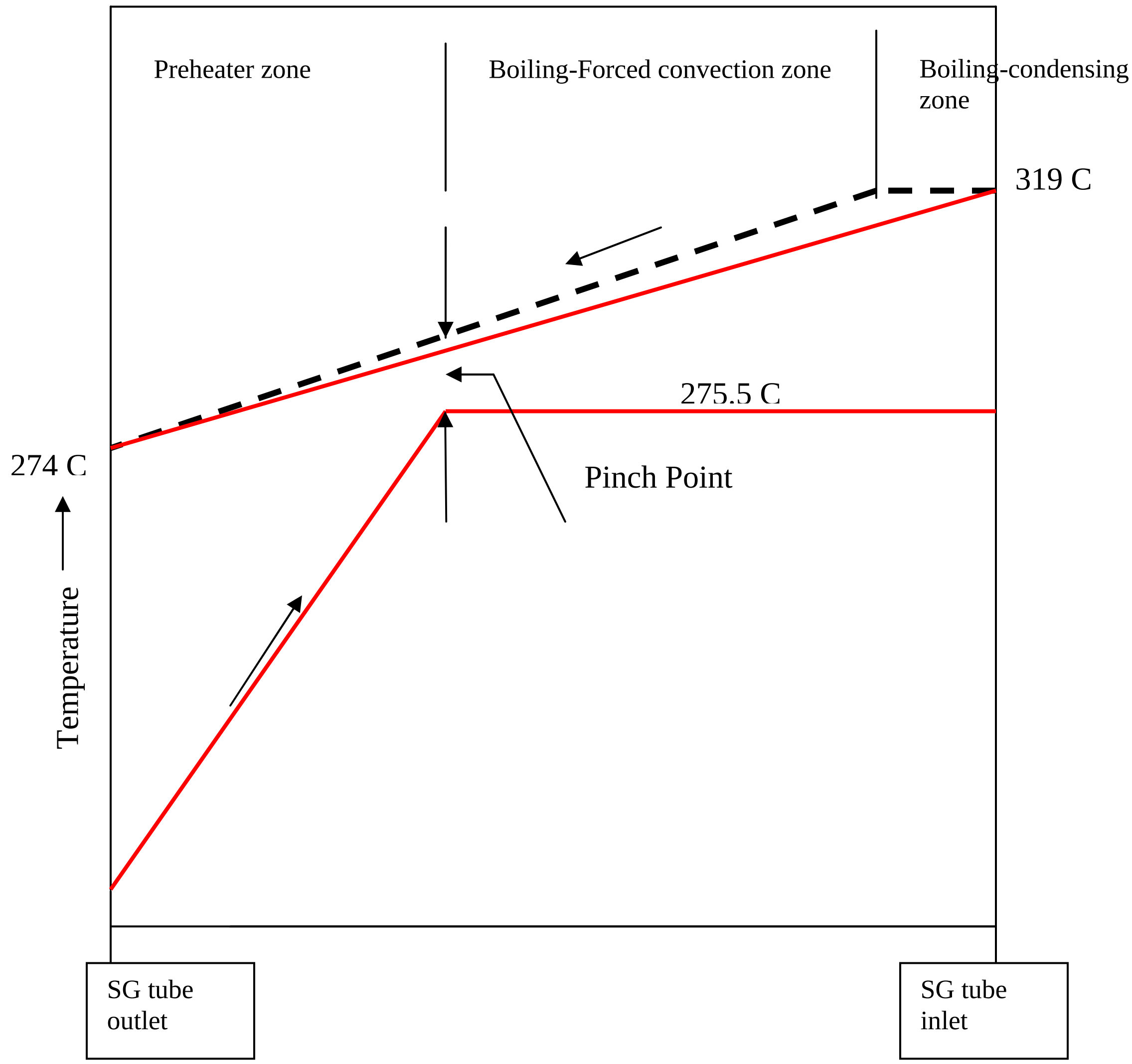

Figure 2 : Temperature diagram for ACR-1000 steam generators

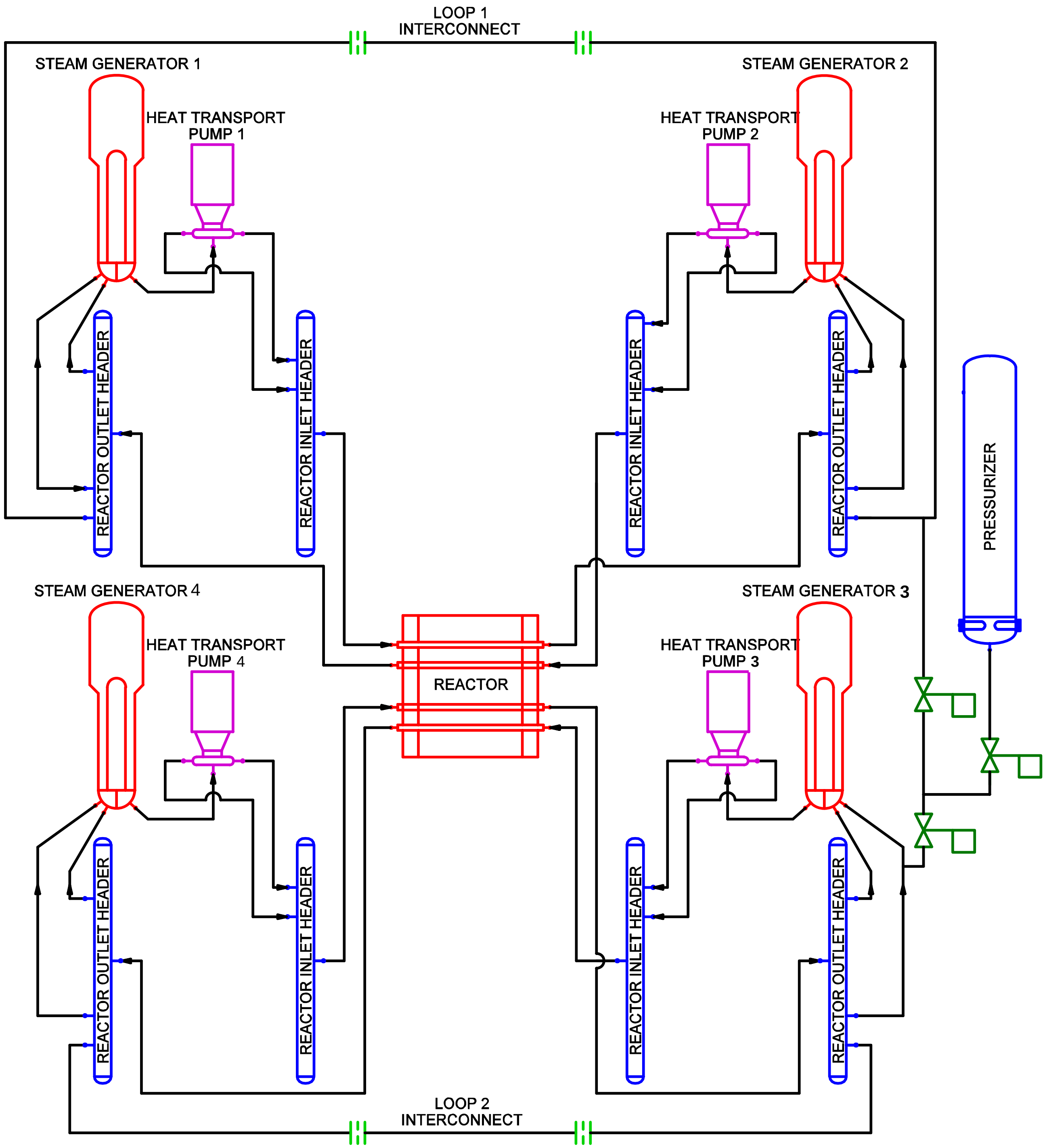

Figure 3: ACR-1000 Heat Transport System

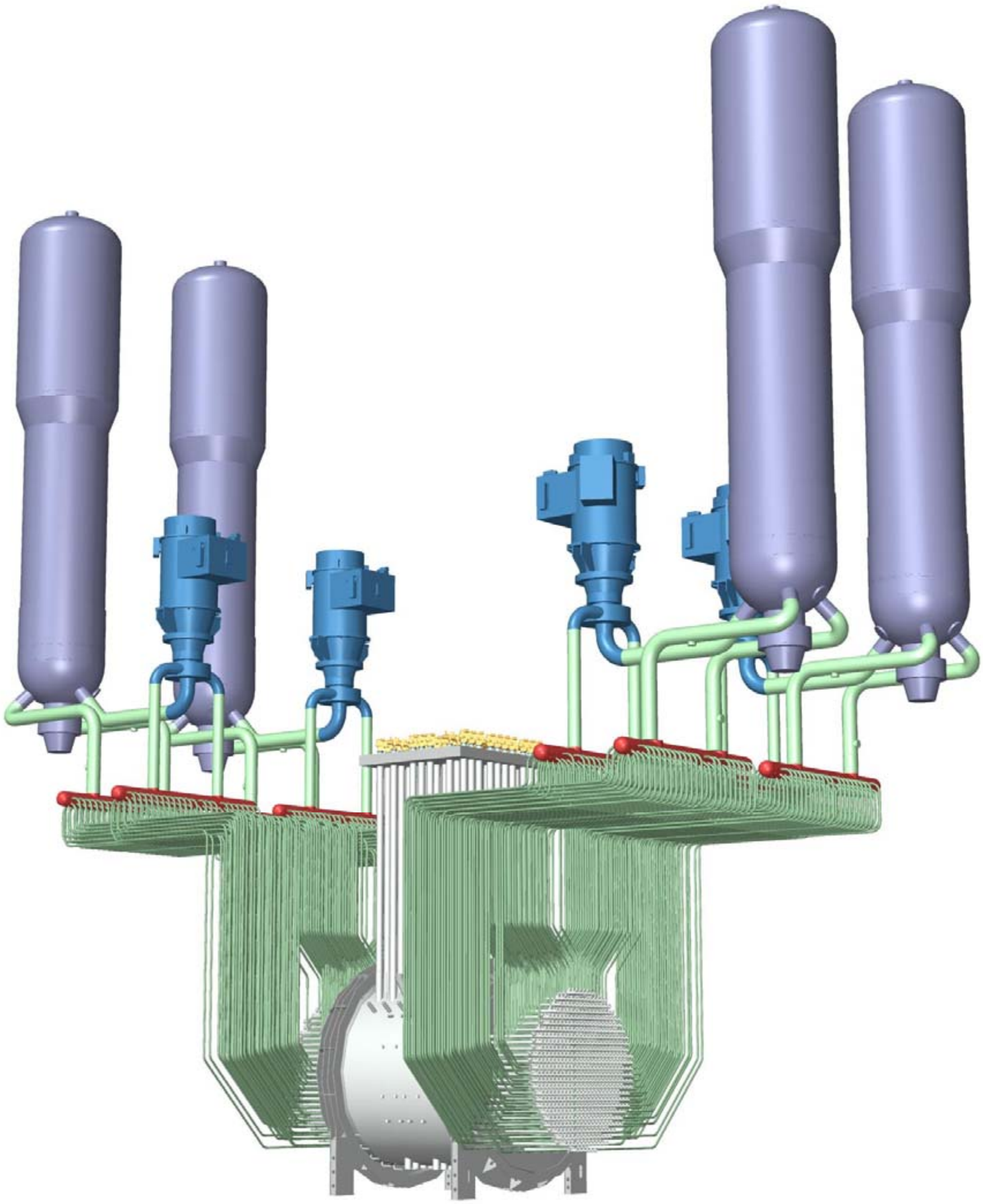

Figure 4: General arrangement of HTS system.

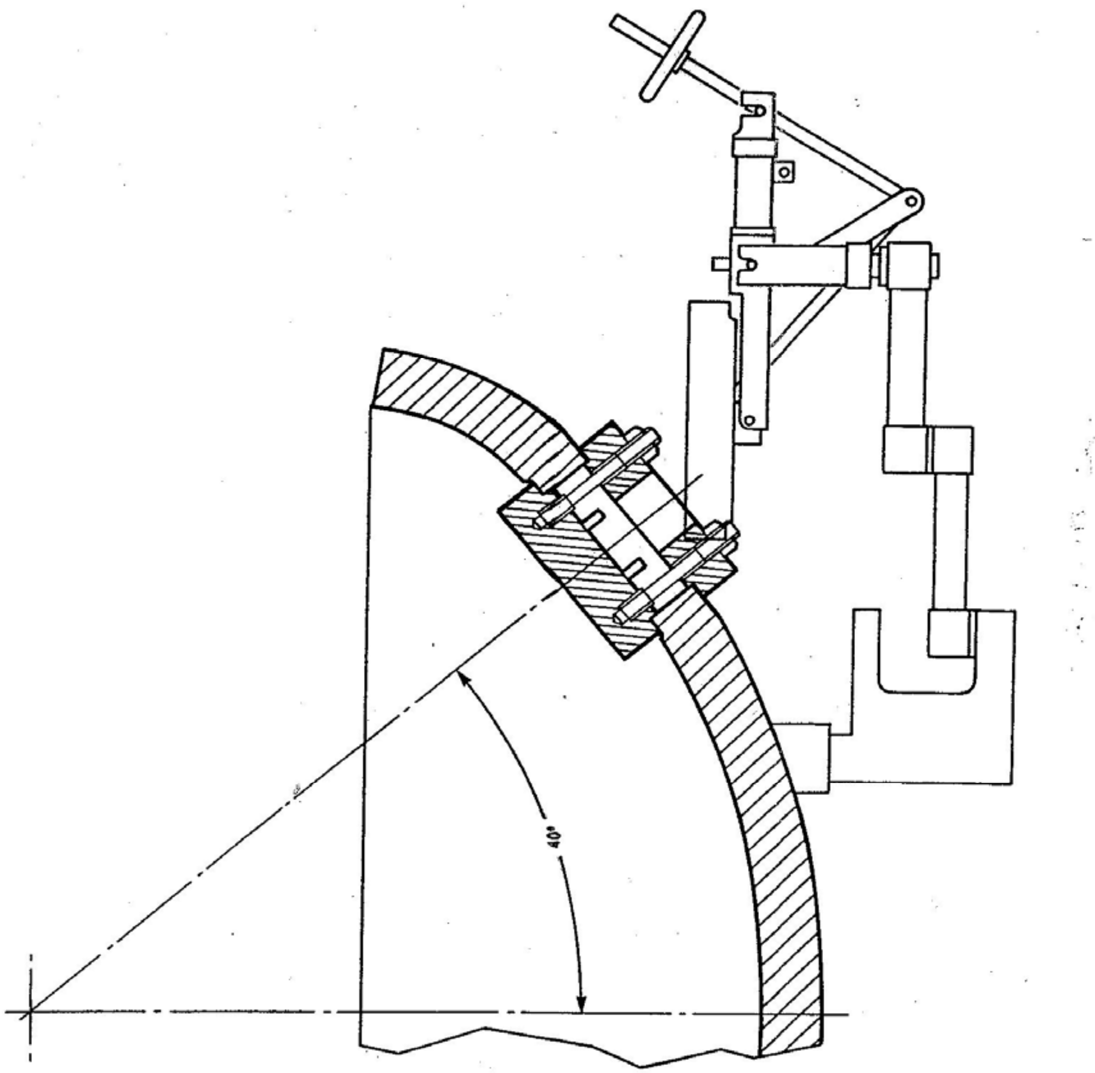

Figure 5: Primary Head access with manway manipulator