STEAM GENERATOR REPLACEMENT AT BRUCE A: APPROACH, RESULTS, & LESSONS LEARNED

W. Tomkiewicz, B. Savage, and J. Smith
SNC-Lavalin Nuclear, Inc.
Oakville, Ontario, Canada

1. Introduction

Steam generator replacements (SGR) have been performed at nearly 100 nuclear power plants throughout the world. However, the steam generators (SG) replaced at Bruce A, Units 1 and 2, were the first for any CANDU plant. Because of Bruce A's unique reactor containment design and steam generator arrangement, SNC-Lavalin Nuclear faced a number of significant technical challenges for successfully completing the replacement. Bruce A is the only CANDU plant with an arrangement of bulbless steam generators connected to a horizontal, integral steam drum. The steam generators also pass through the containment boundary in the reactor vault ceiling. Because of its unique design, it was determined that previous approaches developed for the replacement of steam generators in Pressurized Water Reactors (PWR) would not be feasible, if used directly. To meet this challenge, a unique approach and methodology was developed for the Bruce A SGR project, which adapted certain PWR technologies specifically for this purpose.

This paper describes the unique approach and methodology for the Bruce A steam generator replacement as developed by SLN. The work at Bruce A was essentially completed when the last steam drum was lifted into position on February 3rd, 2008.

2. Replacing the 16 Steam Generators in Two Bruce A Reactors

The layout and geometry of the Bruce A nuclear reactors is as shown in Figures 1, 2, and 3. There are two sets of steam generators connected to each reactor. Each SG set consists of four lower sections connected to one horizontal steam drum (SD). Each SD is 30 m long, 2.9 m in diameter, and weighs 250 tonnes. Each steam generator lower section is 12 m long, 2.4 m in diameter (narrowing to 1.75 m at its upper end), and weighs 100 tonnes. The fundamental reason for replacing the steam generators is the corrosion of the internal steam generator tubing. Since all the internal tubing is contained in the lower SG sections, those assemblies must be replaced. However, the steam drums are not affected and can be re-used.

The reactors at Bruce A have a unique containment design (see Figure 3). Only the lower part of the reactor building (which houses the reactor, feeder assemblies and PHT piping, the lower end of the PHT pumps, the lower end of the steam generators, the pressurizer, and several other vessels that are tied directly to the PHT system) is actually inside the containment structure. The containment itself is connected by underground ducting to the vacuum building, and the reactor re-fuelling machine system. The majority of the steam generators, including blowdown systems, are housed in a "boiler room" that is isolated from the containment by bellows seals and the reactor vault's thick concrete roof. The lower sections of each steam generator pass through the roof of the reactor vault that is 2 m thick.

Between the boiler room and the steam drum enclosure there is another concrete floor with 3 m x 4 m rectangular holes provided for connections from the steam generator to the steam drum. The steam drum itself is contained within the SD enclosure with a roof (0.7 m thick) made of steel and reinforced concrete.

The overall task for this project was to replace the eight steam generators in each of the reactor Units 1 and 2 at the Bruce A plant with like-for-like replacement steam generators, reconnecting them to the steam drums and Primary Heat Transport (PHT) piping, and restoring the plant to "as-found" condition (i.e., returning everything that was removed temporarily to the way it was found).

3. Methodology & Approach

The actual method and approach of how the steam generators would be replaced was the responsibility of the replacement contractor. Several different methods were examined, which included the following possibilities.

1) Taking the steam generators out of the boiler room through holes (to be made) in the 2 m thick side walls of the boiler room;

2) Moving the steam drums, and lifting the steam generator sections by turning them horizontally and removing them through the reactor building North wall;

3) Moving the steam drums, and lifting the steam generators out vertically through the reactor building roof.

Since there was no crane inside the reactor building with the capacity to perform any of the lift methods described above, the replacement of Bruce A's steam generators would require the use of new cranes. For the first two methods, semi-permanent cranes must be set up inside the reactor building. The third method requires either gantry cranes to be mounted on or under the reactor building roof, or a free standing crane positioned on the ground (behind the reactor building) that lowers a hook into the building through the roof to make the vertical lifts.

The concept of a roof-mounted gantry crane system was never developed, as the roof of the reactor building was not specifically designed to support such heavy lifts. Although some temporary supports could be used inside the reactor building, the impact on the schedule would be a significant factor. Also, any structures added within the building and not removed at the end of the project would be subject to additional seismic qualification. These considerations are described in detail in a CNS paper by R.S. Hart (Ref. [1]).

The approved solution involved using a Medium Lift Crane (MLC) positioned on the ground at the North end of the reactor building. This crane (shown in Figures 5 and 6) was capable of making all the required lifts, and could easily reach and lift all the steam generators vertically in and out of their positions. Because of the long reach needed, the lift capacity of this crane was rated at 1800 tons.

Once the crane selection was made, the following logic was used to determine the methodology.

a) To remove the steam generators vertically out through the reactor building roof, the steam drums would be separated (cut) from the steam generators and temporarily moved out of the way. Originally, the steam drums were delivered to site from the manufacturer in two sections that were field welded together. Since they were never lifted before as assembled units, a significant engineering effort was required to assure that the lifts could be executed safely and properly. Many alternatives were considered as to where to place the drums, and how to remove them from the reactor building during the steam generator change-out. The final decision was made to place the drums on elevated saddles (to be designed and constructed) at the inside of the drum enclosures towards the reactor, where the steam drum connections to the replacement steam generators could be machined;

b) To lift out and temporarily relocate the steam drums, the reinforced concrete roof of the steam drum enclosure would be cut into pieces using a special diamond wire cutting process. The cut pieces would then be taken as waste for disposal on site;

c) To remove the steam drums, all connecting piping such as the steam piping, feedwater piping, instrument piping, etc., would be cut, removed, and placed in temporary storage to be re-used later;

d) To remove the steam generators, all connecting piping such as the PHT piping, blow-down system, and instrument piping would be cut. The original seal plate of the bellows seal for each steam generator would then be cut, and replaced by a new seal plate;

e) While the steam generators were still in the reactor building, all open nozzles and man-ways would be sealed with heavy steel covers, as specified for medium term radioactive waste storage. Trunnions would be welded to each steam generator in positions that are comparable to the trunnions supplied with the replacement steam generators. This would permit the same lifting methodology to be used for old steam generator removal and replacement steam generator installation;

f) The generator replacement was performed as follows.

    1) At any steam generator bank, only two SGs were removed at one time. The other two were left in position and remained welded to the PHT piping to stabilize the overall feeder, header, and piping system for that bank of steam

generators. Only after the first two steam generators were replaced and welded to the PHT piping, the second two SGs were cut from the inlet and outlet PHT piping;

2) Pipe restraints were installed at the individual PHT pipe ends and at other strategic locations in the reactor vault, as determined by modeling and stress analysis in order to limit the movement of individual pipe ends, resulting from residual stresses introduced during the original plant's construction;

3) Given the uncertainty of pipe movement after cutting, the replacement steam generators included unmachined PHT nozzles with a considerable amount of extra material in the area of the pipe weld to allow for fitup to the PHT inlet and outlet piping. After the original SGs were removed, the machining of the open PHT pipe ends was finished. Detailed laser metrology was then performed, and the results (i.e., exact pipe end location and orientation) were used to final machine the nozzles of the replacement SGs on site prior to their installation to ensure an exact fit to the pipe ends;

4) Similarly, the replacement steam generators were supplied with extra material at the upper end, where the smaller diameter SG section would be joined to the steam drum nozzles. It was known from ultrasonic examination that according to the ASME minimum wall criteria, there was little extra material in the SD nozzles beyond the minimum Code requirements. For this reason, the fitup adjustment would be made by machining the top end of the SG. However, first and foremost was the PHT nozzle machining;

5) When installed, the steam generators are supported by pedestals on thermally insulating maronite pads and a trapeze assembly which is suspended from the ceiling of the reactor vault by 4 steel rods. The trapeze assemblies support the combined weight of the SGs and steam drums during operation. To ensure that the trapeze assemblies would not move vertically after the weight was removed, restraints were designed and fitted to the trapeze assemblies, thereby locking their position vertically;

6) The horizontal position of the steam generators and PHT piping was maintained by fitting wooden blocks between the 2 generators that must remain in place at any one time, and the concrete vault ceiling penetration to the boiler room above;

7) The pedestals were removed and replaced by new, custom made pedestals that matched their corresponding replacement steam generator. The original maronite pads contained asbestos, and were replaced by their modern asbestos free equivalent;

8) Extensive surveying was performed before any of the replacement activities using modern laser technology to determine the precise locations of the steam

drums, the old steam generators, and the PHT piping. These exact locations established the relationships between the components within a grid coordinate system that was created within the reactor vaults, boiler rooms, and steam drum areas. The replacement steam generators were also surveyed when they arrived on site. The resulting computer model was a 3 dimensional virtual environment, which made it possible for each replacement steam generator to be custom machined outside the reactor building to match all mating PHT piping prior to installation.

g) Pairs of steam generators from each side of the reactor were separated (cut), removed vertically, and transported to Ontario Power Generation's Western Waste Management Facility located within the Bruce site for medium term storage. Measurements of the severed PHT inlet and outlet pipe faces were made to confirm their precise 3 dimensional locations. Following the data processing and analysis, machining instructions were prepared for the PHT pipe ends and matching replacement steam generator nozzles, and the final machining was initiated. The pedestals and pads were removed, their replacements were installed, and the pairs of replacement steam generators were installed. After each generator was gently lowered into place by the MLC, the steam outlet was positioned by the metrology team to match the mating steam drum nozzle and installed bracing, and the PHT pipe welding was started. When the PHT pipe welds were essentially finished, the second pair of steam generators in each bank was replaced following the same procedure;

h) When all the replacement steam generators were installed and the nozzles on the lower side of the drums were final machined, the drums were lifted back on top of the four steam generator banks, and supported temporarily by hydraulic jacks. All four nozzles were perfectly aligned for height, position in the horizontal plane, and orientation to the horizontal plane. Finally, the drum to steam generator welds could be completed;

i) After the drum welds were completed, the concrete roofs of the steam drum enclosures were reconstructed by recreating the steel and reinforcements, and then pouring roughly 220 tonnes of concrete per steam drum. Finally, all the interferences, piping, and insulation were replaced to return the reactor units to “as-found” condition. Both the steam drum enclosures and the reactor building roof (holes) were reconstructed and restored according to the original design. With that, the steam generator assemblies were ready for recommissioning. Full recommissioning and restart will not take place until after the pressure tube replacement and other re-start activities are completed.

4. Results

4.1 Task Completed

As of February, 2008, all of the steam generators at Bruce A reactor Units 1 and 2 are replaced, the drums are repositioned, and the welding is nearing completion. Reconstruction of the drum enclosure roofs is in progress. Pipe replacement, interference replacement, and insulation work will be completed at Unit 2 by June, 2008, and at Unit 1 by September, 2008. This project will be completed with a significant number of first-of-a-kind (FOAK) operations.

4.2 Quality

The overall quality record for the project was excellent. A specific Project QA program was established and approved, with compliance confirmed and maintained through audits. Each reactor Unit required a total of 24 major welds.

4.3 Safety

The significant focus on safety throughout the project included daily safety meetings at site, project safety plans, and detailed reviews of any safety incidents. By January of 2008, and with the project nearing completion, over 1 million person-hours of work have been completed on the job without a lost-time injury.

4.4 Radiation Dose

The Bruce A, Unit 2 SGR project set a world record for lowest collective radiation dose in a steam generator replacement job. The collective dose was measured at 41 man-rem (0.41 man-Sv). This can be compared to a previously claimed record of 57 man-rem at Palo Verde (Unit 2) in the U.S. The Palo Verde project involved the replacement of two steam generators. On a radiation dose per steam generator basis, the Bruce A Unit 2 dose of 5.2 man-rem per steam generator was less than one third of the lowest ever collective radiation dose reported for a PWR replacement (ref. [2]). The collective radiation dose from the Unit 1 replacement was 57 man-rem. Although the dose was approximately 40% higher, the radiation fields (mrem/hr) in the critical areas of Unit 1 were almost double those of Unit 2, so the actual results represented better performance by the work crews and ALARA team (ref. [3]).

4.5 Alignment & Metrology

Alignment and metrology are crucial aspects of any steam generator replacement project. This is particularly true in the case of Bruce A, as a “12 point alignment” was defined for each steam generator bank. In other words, an extremely accurate alignment was needed from the steam generators to their own pipe connections, and to a common assembly with the steam drum. Laser metrology was used extensively for both the location of terminal points, and as a guide for precise machining to match the terminal points. Every component needed to be aligned correctly to within fractions of a millimeter. As the project moved forward and experience was gained in the metrology systems and methods, the metrology factor contributed significantly to the schedule improvements described above. The reconnection of major equipment consisted of the PHT pipe connections in the reactor containment vault, the pipe trunnion and bellows seal connections in the 'boiler room', and the steam generator to drum welds in the steam drum enclosure. The 12 point alignment combined with the alignment of connections from 3 separate rooms resulted in an alignment and metrology process that was considerably more complex than what is commonly seen in steam generator replacements for light water reactors (i.e., 3 or 4 point alignment, single room).

The 40 heavy lifts completed in total during the SGR project consisted of 4 steam drums removed and relocated, 16 old steam generators removed, and 16 replacement steam generators installed. All terminal points were within the specified alignment tolerances from the outset.

5. Summary

The steam generator replacements at Bruce A Units 1 and 2 have now been completed. The overall results were very satisfactory, including the quality, schedule and safety outcomes, and a world record low collective radiation dose. Areas for possible improvement in future SGR projects have been identified. This initial steam generator replacement for a CANDU reactor will provide good metrics and a point of reference for future projects.

A video will be shown as part of the presentation of this paper.

6. References

[1] Hart, R. S., "Steam Generator Replacement in Bruce A Unit 1 and Unit 2", Paper presented to CNS International Steam Generator Conference, Nov. 26-29, 2006;

[2] Global RPM Monitor, "Information System on Occupational Exposure, Steam Generator Benchmarking ISOE Database", Issue: GRPM 01-02, December, 2001;

[3] Khan, Arif*: Personal communication dated April 30, 2008.

*Radiation Protection Manager, AMEC NCL, Bruce A Restart Project.

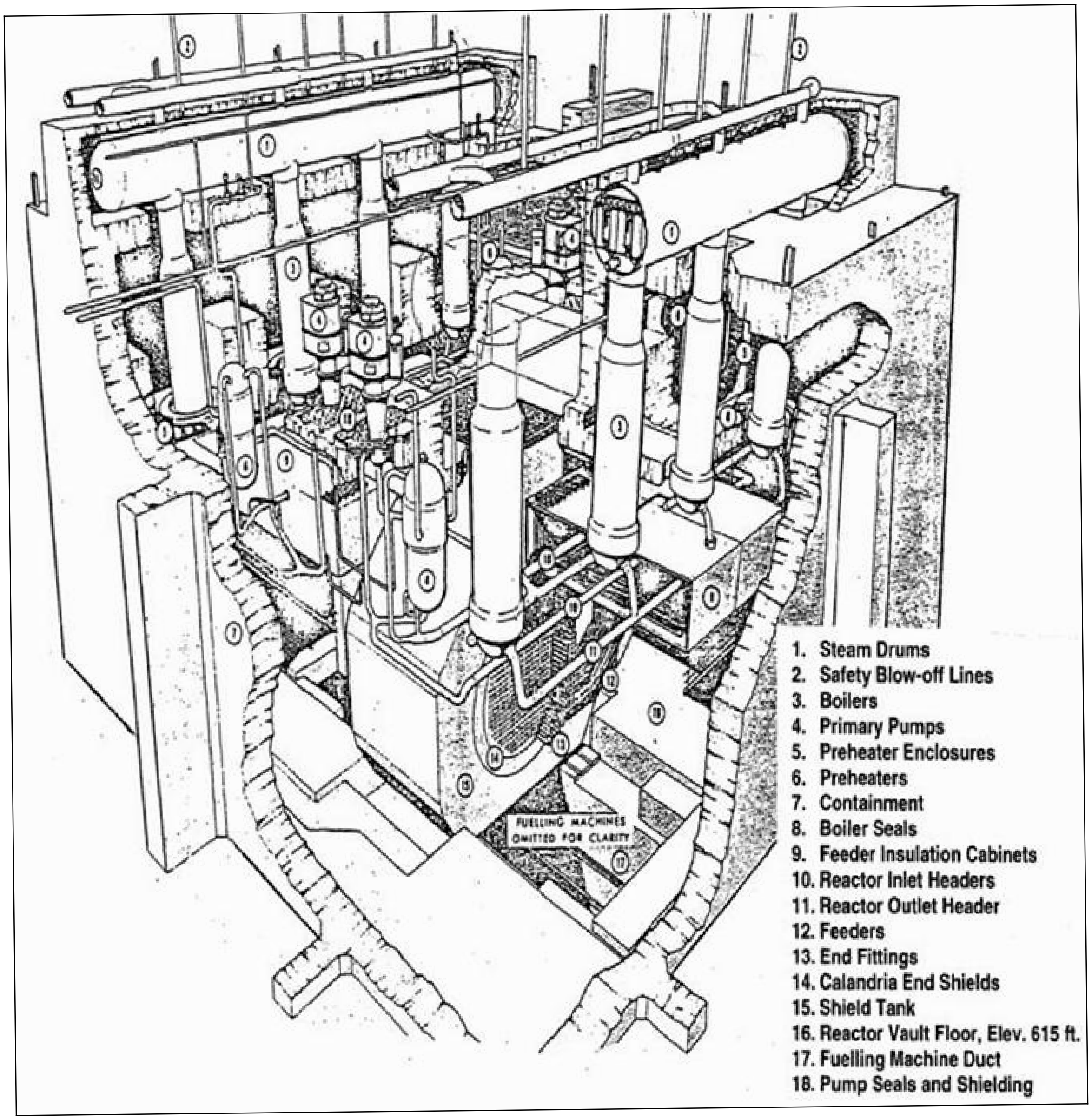

Figure 1, Bruce A Steam Generation Assembly

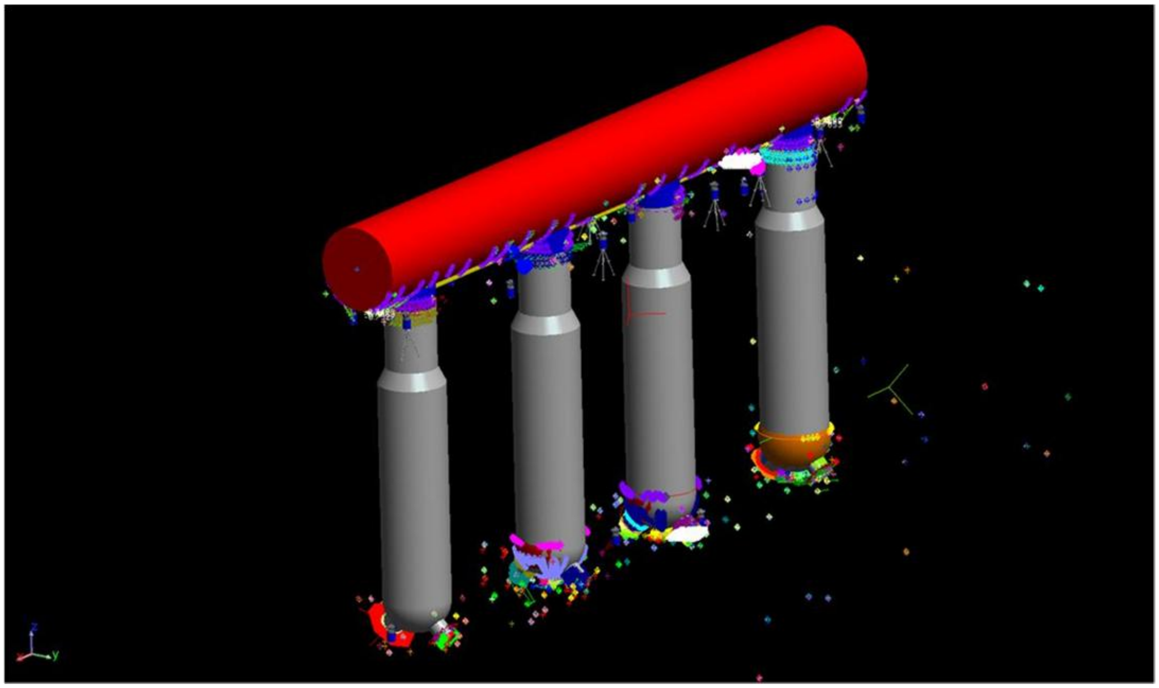

Figure 2, Computer Model of Steam Generators & Steam Drum

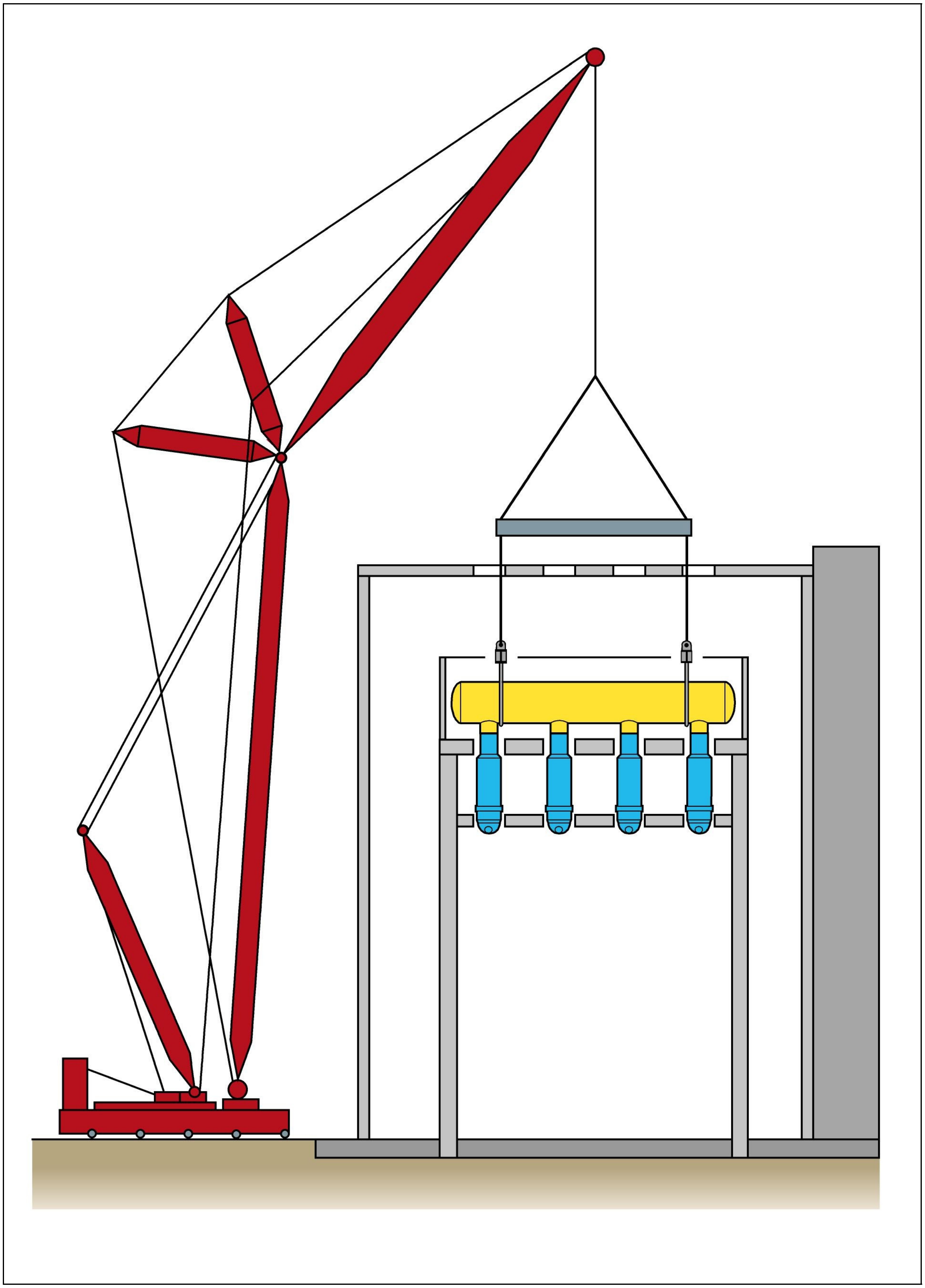

Figure 3, Steam Drum (SD) Repositioning

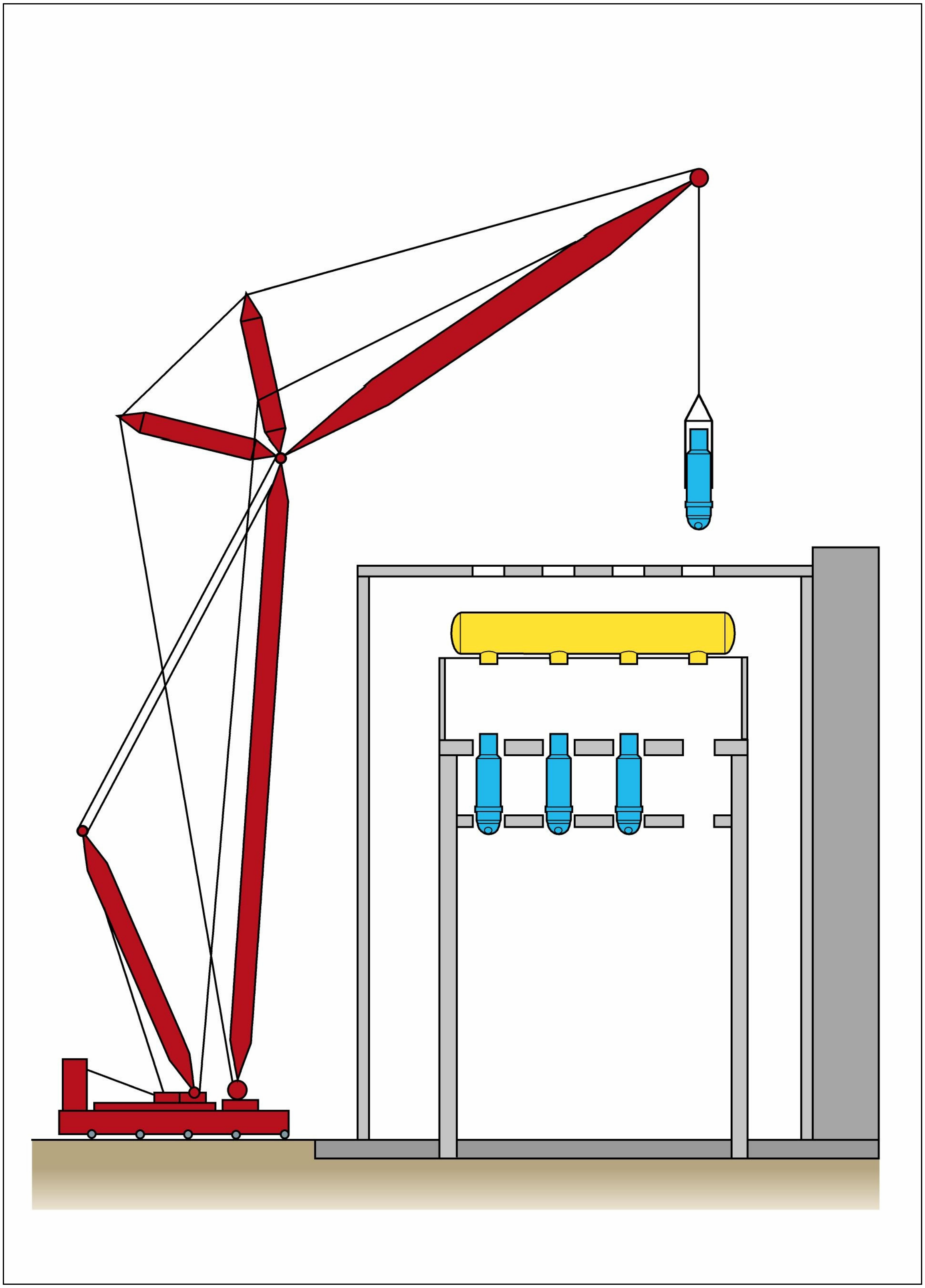

Figure 4, Steam Generator Removal/Replacement

Figure 5, Medium Lift Crane (MLC)

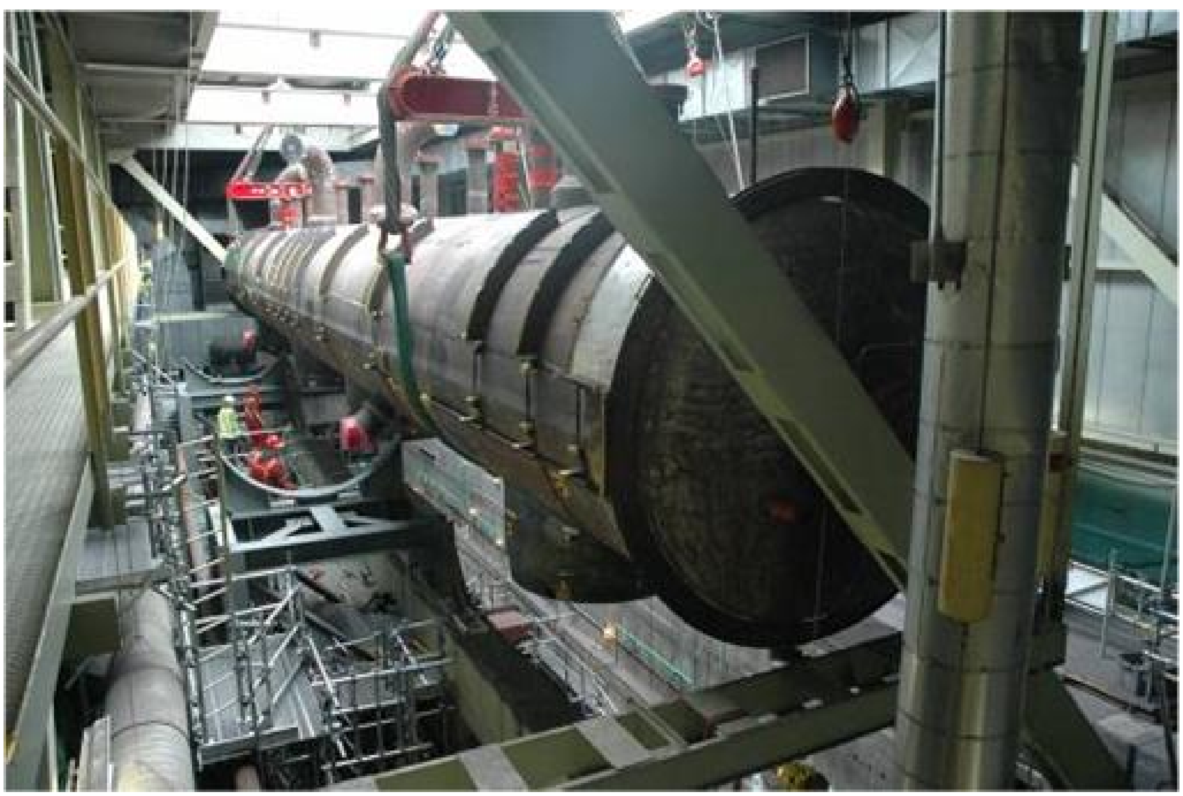

Figure 6, Bruce A Steam Drum