Evolution of CANDU vacuum building and pressure relief structures from Pickering NGS A to Darlington NGS A

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ABSTRACT

The vacuum building (VB) and pressure relief structures (PRS) are the unique features of multiple unit CANDU containments. In case of loss-of-coolant accident, the released radionuclides are drawn through the PRS into the subatmospheric VB, doused and contained without being released to the environment.

This paper describes the differences in design, configuration and layout of the VB and PRS from Pickering NGS A to Darlington NGS A due to new developments in design concepts and to requirements which have proceeded from the experience gained in both the design and operation of the nuclear stations.

1 INTRODUCTION

The Pickering, Bruce and Darlington Nuclear Generating Stations (NGS), vacuum buildings (VB) and pressure relief structures (PRS) are all part of the multi-unit CANDU advanced safety device of a negative pressure containment system, and have the same unique function: that is, after any postulated loss-of-coolant accident (LOCA) the released radioactive products from the reactors are drawn through the PRS into the VB, maintained at subatmospheric level, doused and contained without being released to the atmosphere. However, the three station pressure suppression systems are geometrically and structurally different.

The historical background of the differences in design, configuration and layout of the VB and PRS from Pickering GS A to Darlington GS A and a brief review of this evolutionary process is useful for concept and design work related to future stations.

2 PICKERING NGS A AND B VACUUM BUILDING

The Pickering VB (Figure 1) is a reinforced concrete structure comprised of: (i) a free standing external cylindrical shell, restrained at the bottom, with a stiffening beam at the top; (ii) an internal space frame supporting the roof and water tank; and (iii) a basement which houses the auxiliary equipment and provides access to the underside of the floor of the main vacuum chamber for inspection and maintenance (1,2). The internal structure is free from the perimeter wall except at the roof slab level, where it is connected to the wall by means of a fabric-reinforced elastomeric seal designed to tolerate relative movement in the vertical and horizontal directions. The perimeter wall is 0.9 m thick and 50 m in diameter and height.

The wall was slipformed in early May 1969 with a continuous concrete placing rate averaging about 23 cm per hour. The wall is designed to withstand the following loads: gravity, negative pressure of 98 kPa, local vertical loads applied by the vacuum ducts and dynamic horizontal antisymmetrical loads due to accident, earthquake, wind and temperature.

The critical design condition was obtained by comparing the various combinations of the above loading conditions. The design and analysis of the wall was performed in accordance with the ASME Unfired Pressure Vessel Code and with the method developed by Bergman (3). Using the charts given in the Code, the wall thickness was assumed, such that, when all loads other than negative pressure are applied together with four times the load due to direct compression resulting from the negative pressure, the permissible stress in concrete and steel are not exceeded. The factor four is the factor of safety against buckling or yielding when no other loading exists, and is prescribed by the ASME Code. Stiffeners were added to the wall at the vacuum duct penetration level which is 32 m above the ground, to strengthen and to distribute the unbalanced thrust due to accident.

Wind creates a butterfly-type loading pattern with a positive pressure on the windward quarter and negative on the rest of the circumference. This loading was combined with the negative pressure to arrive at the horizontal bending moment in the wall.

The maximum ground acceleration from earthquake was 0.05 g.

In order to allow the wall to move inward during early thermal shrinkage, a rubber pad was placed at its base with no reinforcing passing through the joint. After allowing six months for thermal displacements, the wall was drypacked in position in October 1969 restraining it against asymmetrical forces, particularly earthquake.

The top of the wall is stiffened by an integral 2.4 m by 1.8 m deep concrete ring beam, prestressed circumferentially and vertically into the wall because the calculations indicated that ovalling due to construction tolerance and unbalanced wind effects could be 6 cm with no stiffener. The elastomeric roof-seal might not be able to accommodate this displacement.

The internal structure is comprised of sixty-one 1.2 m diameter columns placed on a square grid of 6.5 m centres. Horizontal tie beams of 0.6 m by 1.2 m cross-section were cast monolithically with the columns at 7.2 m centres. The internal frame is structurally free from the perimeter wall.

The emergency water tank provides water for the dousing spray in the VB. The tank is 47 m in diameter and has a 0.5 m thick base slab, 0.6 m thick roof slab and 0.5 m thick walls. Two vacuum chambers are located on the building roof. Each vacuum chamber is 2.4 m high, 3.7 m wide and 37 m long.

The floor of the VB is a 0.6 m thick flat slab with shear panels at the top. The internal structure was analyzed as a space frame and the roof and the floor as slab and girder structures. The roof and the floors helped to distribute the horizontal shear to the columns and beams below.

The effect of earthquake on the large mass of water in the tank was analyzed by Housner's method (4), which gave an equivalent mass of 0.7 times the actual mass of the water. This value, combined with the requirements of the National Building Code of Canada, gave a horizontal force of 0.03 times the weight of the water. This force is transferred by the tank's wall to the tank's roof and floor, which, in turn, transmit the forces to the supporting frame.

The entire VB is supported by about 1,000 H-shaped steel piles of 15 m length bearing directly on the underlying bedrock. A 1.5 m thick working slab serves as common pile cap as well as the basement floor slab.

3 BRUCE NGS A & B VACUUM BUILDING

In essence, the Bruce VB (Figure 2) possesses the same basic structural elements as the Pickering VB, but with certain modifications, such as circumferential prestressing of the perimeter wall, an elastomeric roof-seal held in position by post-tensioned tendons for better efficiency and elimination of the stiffeners since no vacuum ducts penetrated through the perimeter wall.

The main vacuum chamber is a circular building having a diameter of 49 m and a height of 45 m. The method of analysis and design of the 1.1 m thick perimeter wall is the same as that used for Pickering except that the Bruce wall was also designed for internal positive pressure. The post-tensioning tendons were placed horizontally to accommodate the maximum accident pressure of 48 kPa and to ensure leaktightness. Since the wall at Bruce was thicker than at Pickering, a ring girder was not required at its top.

As at Pickering, the emergency water tank, the roof and the vacuum chambers are all supported by the internal space frame of columns and beams. The upper vacuum chamber, which is 12 m in diameter and 6 m in height, is formed of reinforced concrete with 0.9 m thick wall and is located centrally on the roof. The lower vacuum chamber placed below the water tank floor is supported by four 1.5 m thick walls which, in turn, rest on the columns of the internal space frame. The basement is made higher than at Pickering in order to accommodate the vacuum ducts. It contains shear walls to resist horizontal forces. The design procedure of the internal structure is similar to that at Pickering. The foundation slab rests directly on the bedrock.

4 DARLINGTON NGS VACUUM BUILDING

The design of the Darlington VB (Figure 3) differs significantly from those of Pickering and Bruce because of the requirement to contain higher positive pressure, to eliminate difficulties associated with the manfacture and supply of roof seal, and due to site related high hydrostatic pressure (5). The main vacuum chamber was formed by a 48 m diameter cylindrical perimeter wall, having a fixed support at the structural foundation slab and a spherical roof dome connected monolithically to a peripheral ring girder, thus eliminating the roof seal connection. The 1.2 m thick wall and the 3 m by 6 m deep ring girder are prestressed both circumferentially and vertically. The dome is prestressed by three families of tendons lying in great circles and oriented 120 degrees apart. The prestressing was done by unbonded greased tendons. A gallery in the foundation slab provided access to the dead-end anchorages of the post-tensioning cables. The floor slab and the lower 6 m of the perimeter wall are lined with carbon steel, thus reducing the possibility of leakage.

Numerous combinations of pressure, temperature, shrinkage, creep, hydrostatic, seismic, prestress and self-weight were considered in accordance with the CAN3-N287.3-M82 Code. The analysis of the outer containment shell was carried out using the MSC/NASTRAN finite-element program. Both axisymmetric and non-axisymmetric models were utilized to handle the different loads. A lumped-mass dynamic model provided the seismic response.

The stability of the containment shell was evaluated by two approaches. In one, the recommendations of the International Association for Shell and Spatial Structures was used. In the other approach, the theoretical upper bound buckling capacity of the cylindrical wall and spherical dome was reduced to lower bound values by imposing factors accounting for geometric imperfections, cracking and non-linear behaviour of the concrete. Both methods of analysis indicated that crushing failure would occur before buckling.

The internal structure supports the dousing tank and is comprised of a cylindrical shell and a circular space frame of columns tied by ring beams at two elevations. Vacuum chambers rest on the inner shell. The major long-term loads for the internal structural assembly are the dead weight and the water mass, while the important short-term loading is earthquake. The tank was treated as plates or shells and the cylindrical support was analyzed as a beam having a large end mass and resisting the entire lateral seismic force. The introduction of the columns altered the behaviour of the central support from one of single curvature cantilever behaviour to a state of double curvature. The columns and horizontal tie beams were analyzed as a space frame.

The Darlington VB does not have any basement. The base slab is solid with embedded ducts and had to be 8 m thick in order to counteract substantial hydrostatic uplift and a higher seismic ground acceleration which is 0.08 g compared to 0.05 g at Bruce.

5 PRESSURE RELIEF STRUCTURES

These are part of the pressure relief system which interconnects the reactor buildings (RB) and the VBs, and house the pressure relief valves (PRV) which isolate the atmosphere of PRS from that of the VB during normal operating conditions. In Pickering because of the unitized concept, a pressure panel system isolates the atmosphere of each RB from that of the PRS. Eight RBs of Pickering are connected to the VB by a pressure relief duct (PRD) running along the RBs. The PRD which is PRS in case of Pickering is an elevated 6 m by 8 m high and 0.8 m thick rectangular, reinforced concrete structure supported on 25 m high concrete frames spaced at about 27 m and bearing on steel piles. The duct is simply supported on the frames with the hinged end being achieved by continuous reinforcement in the floor slab only and the free ends slide over lubrite bearings and have expansion/contraction joints.

The Pickering PRD is connected to the VB by twelve 1.8 m diameter "U"-shaped steel vacuum ducts, and to each RB by a 2.4 m long reinforced concrete cylinder having a diameter of 8 m and a wall thickness of 0.6 m. The RB end of this short cylinder is monolithically cast, but the other end is provided with a special joint which can transfer forces across the joint at the same time accommodating differential movements between the duct and the RB. The openings of the cylinders are blocked by bulkhead rupture panels (Pickering B) which permit only outward flow of the LOCA-induced pressures from a RB into the pressure relief system. The vacuum ducts are provided with valves which activate automatically when pressure differentials reach a preset value. The PRDs are designed for both a positive pressure of 41 kPa and a negative pressure of 55 kPa.

In the case of Bruce, a partially steel lined fuelling machine duct (FMD) runs underneath the four reactor vaults providing access for the fuelling machines as well as acting as part of the pressure relief system. Two PRDs branch out laterally from the FMD midway between the reactors, emerge above the ground through a transition zone and join a single pressure relief valve manifold (PRVM). For an improved PRVs' layout and better distribution of the loads during a LOCA, the PRVM circumscribes the VB for about 200 degrees and is formed by the upper part of a two-celled box structure which is subdivided into several segments by expansion/contraction joints. Each individual segment is capable of resisting seismic forces independently with the help of radial shear walls in the lower cell. Eighteen 2 m diameter "U"-shaped vacuum ducts connect the PRVM with the VB. The superstructures of PRVM and VB are independent, their basements are interconnected and they rest on a common foundation.

Although the layout is similar, the Darlington PRS is subjected to much higher loads than those at Bruce. In Darlington, the FMD and PRD are fully lined with steel. The PRVM structure circumscribes the entire VB and is completely independent of the VB, only joined by shear key at the foundation level. The foundation slab is tied to the bedrock underneath by means of prestressed and non-prestressed anchors, the former resisting the sustained hydrostatic load and the latter counteracting short-term seismic overturning moments.

6 SUMMARY

The experience acquired through the design and operation of nuclear stations has promoted the development both in design and arrangement of the VB and PRS for multi-unit NGS. For brevity, other minor modifications of the VB and PRS are not mentioned. This review of the chronological development of salient features provides an improved design perspective of these structures which evolved in response to enhanced safety associated design requirements coupled with construction and operational experience. This provides a better understanding for the present of what has been done, and a guiding rationale for the future design of these structures.

7 ACKNOWLEDGEMENT

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8 REFERENCES

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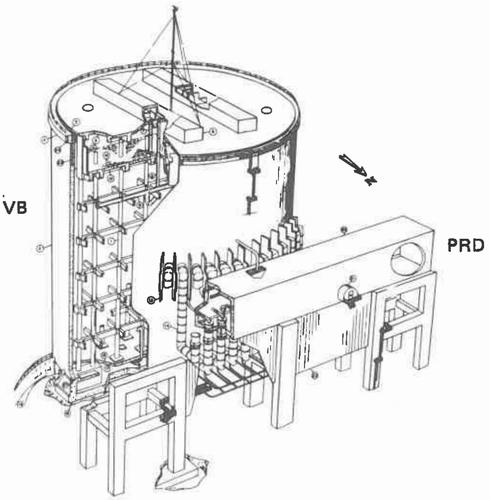

FIGURE 1
Pickering NGS
Vacuum Building and
Pressure Relief Structure

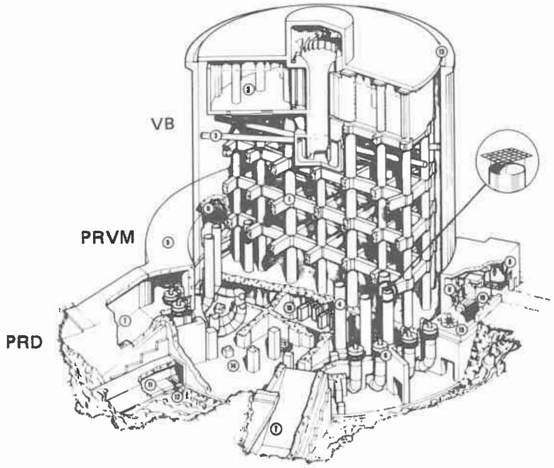

FIGURE 2
Bruce NGS
Vacuum Building and
Pressure Relief Structure

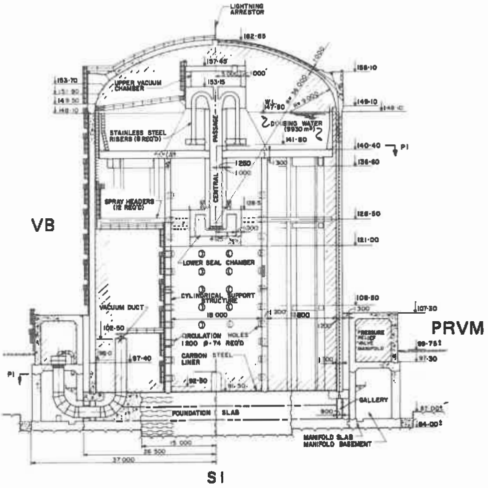

FIGURE 3
Darlington NGS
Vacuum Building and
Pressure Relief Structure