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STUDY ON FEASIBILITY OF A LARGE SIZE STEEL CONTAINMENT VESSEL STRUCTURE TO AVOID POST-WELD HEAT TREAMENT

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ABSTRACT

The passive containment system is an important part of AP1000 to realize passive safety, which consists of cylindrical steel containment vessel, concrete shielding structure and containment air baffle. In the system, the steel containment vessel has two functions, that is, acting as the third barrier of radioactive substance and heat exchanger. When LOCA or MSLB happens, cooling water from the tank above the containment will fall and vapour along the outer surface of the containment while cooling air from outside of the air baffle will flow up through natural cycle channel to take away hot vapour to prevent overpressure.

Thickness of most part of the steel containment vessel is about 44mm, the value under which no post-weld heat treatment is needed for welded-joints of SA738Gr.B steel plate according to ASME III NE. If power of a reactor is greater than that of AP1000, larger volume and greater diameter of steel containment is required. It means that the thickness of the containment vessel has to be greater than 44mm. and post-weld heat treatment is needed.

This paper will present the idea of a new steel containment structure to try to avoid the post-weld heat treatment. Besides, the feasibility analysis of the structure is also given.

KEY WORDS: Steel containment vessel, structure, welded-joint, post-weld heat treatment

INTRODUCTION

As the last barrier to contain radioactive materials released from the reactor core of the primary loop, the containment vessel in nuclear power plants is necessary to keep the public safe from the release of radioactive substances. In the history of nuclear power plants, the Three Mile Island accident and the Chernobyl accident are the two most serious accidents. The two accidents have shown that whether there is containment is crucial for the radiation hazards (Pu Jilong, 1992). As a result, there is a high degree of consensus in nuclear industry on the need for containment vessel. Since the commercialization of the second generation nuclear power plant, there have been many kinds and forms of containment vessels, which vary flexibly with the reactor type, design reference accident parameters, plant site and other specific conditions. However, in general, most of the existing containment systems are active systems. It is difficult to guarantee the safety of nuclear power plants under extreme accidents. With the birth and operation of the third generation nuclear power plant, a series of researches on passive containment system have been carried out.

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The AP1000 containment system is a typical passive steel containment system, its safety function is mainly realized by water film heat transfer and air natural convection to remove internal heat and reduce internal pressure. The system mainly consists of three components: a steel containment vessel, containment air baffle, a shielding structure around the steel containment to provide protection against external projectile damage.

As a heat transfer interface for the final heat sink (ambient and external cooling water), the steel containment is an integral part of the passive containment cooling system. The outer surface can provide the evaporative cooling of the liquid film under the design reference accident condition, as well as the natural convection of the air through the integrated arrangement of the outer shielding structure, diversion coaming, roof and so on, thus reducing the temperature and pressure in the containment vessel.

The steel containment vessel is an independent cylindrical steel vessel with upper and lower ellipsoidal container heads. It is designed and manufactured according to the requirements of ASME III NE (The American Society of Mechanical Engineers, 2004). Diameter and height of the containment are 39.62m and 65.63m, respectively. The thickness of most cylinders in the steel containment vessel is 44.45 mm. The thickness of the cylindrical shell of the lowest containment vessel ring has been increased to 47.62 mm, thus providing corrosion allowance for the buried transition area. The thickness of the container head is 41.27 mm. The container head is an ellipsoidal shell with a diameter of 39.62 mm and a height of 11.47m (Lin Chengge, et al.). According to ASME III NE, no post-weld heat treatment is needed if the wall thickness of the containment is less than 44mm. So only the lowest containment vessel ring needs to be post-weld heat treated.

With the development of nuclear industry, the power of the nuclear power plant tends to be larger. If power of a reactor is greater than that of AP1000, larger volume and greater diameter of steel containment is required. Taking CAP1400 as an example, its steel containment vessel is a cylindrical vessel, the inner diameter of which is 43m and the overall height 73.6m. The material of the containment is as same as that of AP1000, that is, SA738Gr.B steel plate. The construction process is divided into 5 assembly sections, followed by the next container head, the cylinder ring one, the cylinder ring two, the cylinder ring three and the upper container head. The container heads are made up of 82 pieces of 43 mm thickness flap, and the cylindrical shell is made up of 144 curved plates, of which the thickness of the first ring is 55 mm and the remaining 11 rings are 52 mm. Although the CASE N-841 has been published to increase the post-weld heat treatment (PWHT) exemption to a maximum thickness of 60 mm, the NRC has not yet approved a case for this specification to be used on steel containment vessel (Dong Yongzhi, et al.). In such a case, the PWHT is needed for CAP1400 welded-joints. The circumferential weld of the cylinder section should be heat treated after whole circle welding. Considering the process needs large electric power, the construction difficulty and the risk could be very big, and the improper control will bring the bigger security hidden danger.

This paper will present the idea of a new steel containment structure to try to avoid the PWHT. Besides, the feasibility analysis of the structure is also given.

BASIC IDEA OF THE NEW STEEL CONTAINMENT STRUCTURE

The basic idea to exempt the steel containment vessel from post-weld heat treatment is to transform the diversion coaming between the outer side of the steel containment vessel and the concrete shielding structure into an outer cylindrical shell which can bear part of the load generated by the internal pressure, a supporting member is arranged between the outer cylindrical shell and the steel containment vessel to transfer load and form a cooling passage of air and water film. The outer shell, the steel containment vessel and the supporting member form a double-shell structure to bear the internal pressure of the steel containment vessel.

The double-shell structure has the following advantages over the original single-shell structure:

1) Although the thickness of each shell can be limited to the maximum thickness of 44 mm without post-weld heat treatment, the effective thickness of the integral shell structure increases, allowing

higher design internal pressure or larger containment volume due to the load-bearing function of the steel containment vessel and the outer shell.

2) Some form of supporting member is required in order to transfer the load between the steel containment vessel and the outer shell. Not only to set aside space for cooling air and water film, the supporting members also may play a role in enhancing heat transfer.

In the double-shell structure, the steel containment vessel directly faces the internal pressure load, and the outer shell shares part of the steel containment vessel load. However, the upper container head of the outer shell needs a hole of a certain size to act as a opening for air to be discharged into the atmosphere, and also for the containment spray system to spray the cooling water of the storage tank to the top of the steel containment vessel container head.

LAYOUT DESIGN

According to the idea, the new passive containment system still keeps its original function, that is, to perform containment of radioactive material from the reactor core of the primary loop, and to provide better heat transfer performance in accident condition. The new containment system consists of the shielding structure, the outer shell, supporting members and the steel containment vessel. Supporting members are arranged between the outer shell and the steel containment vessel to play the role of transferring load and to form cooling air passages under accident conditions. The outer shell divides the annular space between the outer surface of the steel containment vessel and the inner surface of the shielding structure into two parts: the down-flow outer annulus and the up-flow inner annulus. Air passing through the inner annulus of the upwelling is discharged into the atmosphere from an air diffuser in the middle of the top of the shielding structure. The functional requirements of the outer shell include:

1) Minimize pressure drop as air flows through the system;

2) Allow visual inspection of the outer shell, supporting members and the steel containment vessel.

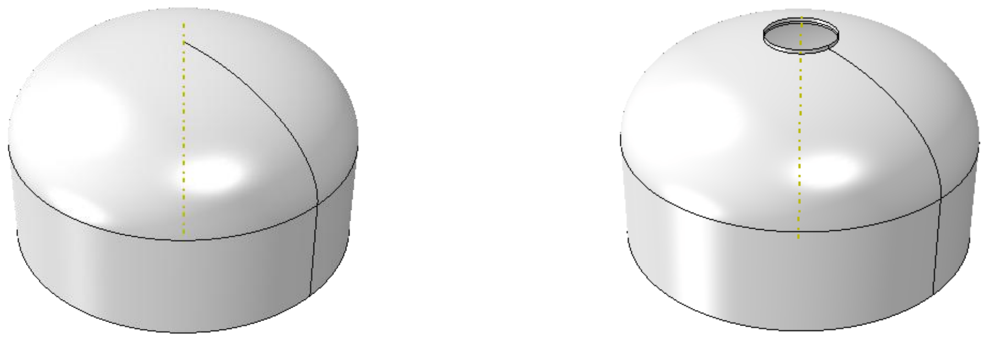
In the new containment system, the outer shell is a steel cylindrical shell and supporting member attached to the outer shell. There is a gap between the supporting members and the steel containment vessel to reduce the thermal stress when LOCA or MSLB occurs. The internal pressure load under the accident condition is borne by the steel containment vessel, supporting member and outer shell together.

In addition to bearing internal pressure, the heat transfer function of passive containment system needs to be realized. For this reason, the upper portion of the containment vessel must be constructed of steel which conducts heat well and is much thinner than the concrete wall. However, as specified in ASME code, for SA738 Gr.B, the maximum wall thickness limit of all plates used in the upper part of the steel containment vessel without post-weld heat treatment shall not exceed 44 mm.

In the event of a LOCA or MSLB accident, most of the huge amounts of energy from the core are released into the containment vessel space as high temperature water vapour. And the water vapour is subject to natural convection and forms flow cycle in the whole inner space height range. Therefore, as the heat transfer boundary, the steel containment vessel is in contact with air and water and plays a decisive role in heat transfer. The heat of the warmer updraft is carried away by convection heat transfer between the water vapour and the steel containment vessel, including its upper container head. The outer surface of the steel containment vessel below the heat transfer part of the steel containment vessel is not in contact with cooling air and water, therefore does not participate in heat transfer process.

STRUCTURE DESIGN

Figure 1 gives the diagram of double shell structure of the steel containment vessel and outer shell thickness of which is less or equal to 44mm. In the double shell structure, a supporting member between the steel containment vessel and outer shell is a variable factor. The design of the supporting member adheres to the roles as follows:



(a) The steel containment vessel (b) The outer shell

Figure 1 Schematic diagram of the steel containment vessel and outer shell

1) Mechanical properties: the supporting member can limit the expansion of the steel containment vessel after internal pressure and high temperature heating, and reduce the most critical membrane stress on the steel containment vessel, thus providing the possibility to reduce the thickness of the steel plate to meet the design requirements. At the same time, the supporting member can effectively transfer the radial load from the steel containment vessel to the outer shell, so that the outer shell is fully and evenly loaded, thus strengthening the integrity of the whole double shell structure.
2) Heat transfer characteristics: the new passive containment system works by heat transfer between air and water film to remove heat from the interior of the steel containment vessel, so the falling of water film and the rising of air play a crucial role. If the flow of both is seriously disrupted, passive safety will be out of the question. The structural form of the supporting member must not obstruct the flow of air and the formation of water membrane, which can ensure the steel containment vessel as a stable and effective heat exchange interface.
3) Operability: The structural form of the supporting member, after satisfying the above two roles, had better have the characteristics of simple manufacture, convenient construction, low cost, etc…

The analysis method is as follows:

1) The whole finite element model of the double-shell structure is established, in which the thickness of the steel containment vessel, the outer shell and the supporting member is less or equal to 44mm. In the finite element calculation, for the reason of conservative consideration, steel plate thickness of which is 44mm is used to verify whether the double -shell structure can meet the requirements of ASME code under the thickness.
2) Material of the supporting member and the outer shell is SA537 Cl.2.
3) Assume the internal pressure of large steel containment is 0.41MPa.
4) Assume the inner diameter of the inner steel shell is 46.5mm.
5) By applying internal pressure load and temperature load, the Mises stress distribution nephogram on each component is obtained, and verified with the terms of ASME III NE and ASME III NF.
6) If the maximum Mises stress on the component is lower than the corresponding stress intensity limit in the steel containment vessel, the supporting member and the outer shell, then the temperature load will continue to be applied on the basis of the constant internal pressure load, repeated calculation and verification.

Three possible design solutions to fulfil the functional requirements of the supporting member are tried and numerically analyzed (Zhu Xinyu, 2014). One of the options is a box-type supporting member.

The continuous box-type structure means that the cross-section of the supporting member is an enclosed approximate rectangle. Thickness of the plate is 44mm. Figure 2 is the schematic diagram of the box supporting member and figure 3 their layout between the steel containment vessel and the outer shell.

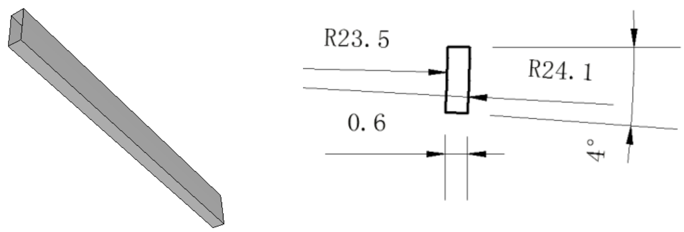
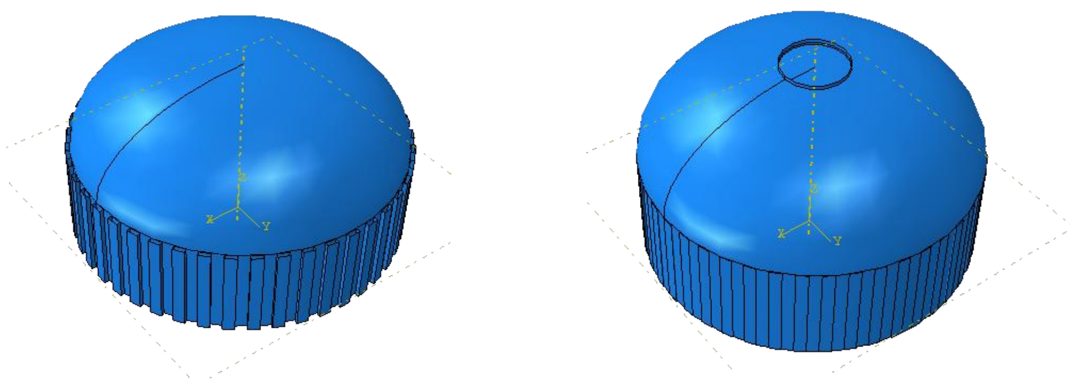


Figure 2 Schematic diagram of box-type supporting member



(a) steel containment vessel (b) steel containment vessel and outer shell

Figure 3 Schematic diagram of the double-shell structure

As can be seen from the schematic diagram, each box-type supporting member consists of 2 curved steel plates and 2 straight steel plates. In order to form the box structure, the arc steel plate and the straight steel plate can be welded or can also be made by metal forming of wider steel plate. Besides，box-type supporting members are divided into longitudinal-upward multi-section ones.

However, unlike other type supporting members, one of the curved surfaces of the box-type members is only fixedly connected with the inner surface of the outer shell either by welding or mechanical connections such as bolt connections, the other curved surface of the box-type supporting member is not rigidly connected with the outer surface of the steel containment vessel, and even has a certain gap with the steel containment vessel. The other curved surface is not connected with the steel containment vessel to allow it to deform under the action of both internal pressure and thermal expansion, which will buffer part of the deformation caused by thermal expansion, thereby reducing the membrane stress of the outer shell. In this respect, the box-type supporting members make up for the shortcomings of the other-type members. That is, because of the existence of the curved steel plate, the straight steel plate does not act directly on the outer shell like a knife blade to transfer the load, at the same time, the stress distribution on the steel containment vessel and the outer shell is more uniform and the phenomenon of stress concentration is greatly reduced. The calculation results show that the Mises stress value of all the components is lower than the stress intensity limit under the internal pressure of 0.41MPa and the temperature load of 150℃ of the steel containment vessel.

In addition, the box-type supporting members also do not destroy the cooling air and falling water film flow. The box-type supporting members themselves surrounded by the channel space and the space between adjacent supporting members all can be used as the cooling medium of the channel. The use of box-type supporting members, compared with other type supporting members, can greatly reduce the number of supporting members, thus vacating a larger cooling medium channel space and not to seriously damaging the air flow.

The box-type supporting members are only arranged in the height of the outer shell, while the upper container head of the steel containment vessel is still a single-layer shell structure. After the height of container head of the steel containment vessel is properly determined and the clearance between the inner shell and the box-type supporting parts is set to 30mm, the stress analysis is conducted. The results have shown that the stress distributions of the steel containment vessel, supporting members and the outer shell meet the design requirements of ASME III NE and ASME III NF (The American Society of Mechanical Engineers, 2004).

CONCLUSIONS

The feasibility of using the double-layer structure to realize the manufacture of large-scale steel containment vessel without post-weld heat treatment is explored in this paper. The main work and results are as follows:

1) The double-shell structure is designed for the upper part of the containment vessel. A double-shell structure model was established to analyze the stress distribution of the components of the double-shell structure under the combined action of internal pressure and temperature. ASME III NE and ASME III NF are used to verify the relevant provisions. The results show that the initial scheme of the double-shell structure can meet the requirements of the stress limit values when the thickness of the steel plate is less or equal to 44mm.
2) The equivalent static method is used to analyze the seismic load of the steel containment vessel with ring-suspended beam. The results show that the thinner steel containment vessel can ensure the safety under the seismic load of 0.3g.

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