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Design of floating nuclear power plant containment under marine environment conditions

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Abstract: [**Objectives**] After several decades of the development and operation experience of military ships, the safety of floating reactors has been greatly improved. Their promotion and application in the civilian field has been gradually recognized, and it is urgently necessary to solve the problem of adaptability in reactor loading on ships. The containment is the interface between the reactor and the hull, and consists of the compartment of the reactor loading on a ship. The containment design must be adapted to the marine environment conditions of the ship, as well as to the nuclear safety requirements of reactor operation. [**Methods**] First, based on the adaptability requirements of floating reactor containment, the main contradiction between the pressure of the containment and the dimensions and weight of the ship is analyzed. A design and analysis process for floating reactor containment is proposed. With reference to the characteristics of onshore nuclear power plants and nuclear power ship containment, as well as the design requirements of foreign nuclear power ships and civil nuclear facilities, a square double-shell suppression containment is proposed in the dimensions of the containment configuration and pressure control program. [**Results**] Through an analysis of the pressure characteristics and structural strength of the containment, the structure of the containment under designbased accident conditions is found to be safe, with controllable weight and space indicators, and a good ship's reactor fit. [**Conclusions**] With reference to engineering experience, the overall index of a floating nuclear power plant based on this scheme is reasonable, and it can provide reference for engineering personnel.

Key words: floating nuclear power plant (FNPP); containment; marine environment; overall design

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0 Introduction

In recent years, a small mobile floating nuclear power plant (FNPP) is quietly emerging to solve the problems of power supply, urban heat supply, and seawater desalination in remote areas around the world [1]. The US government has been funding the development of small reactors since the 1990s, and so far, about 50 small reactor design methods and concepts have been proposed worldwide[2]. Small modular pressurized water reactors including mPower and NuScale in the US, OKBM in Russia, and SMART in South Korea are in the stage of applying the review, and may be approved for construction in the near future[3]. In China, ACP100, CAP150, and ACPR50S small reactors have shown broad application prospects in the fields of FNPP at sea and urban heat supply. In the field of small reactor application research, a large number of feasibility studies and scheme designs of intrinsic safety, passivity and fuel recycling have been carried out, focusing on nuclear safety, nuclear nonproliferation, radioactive waste

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management, effective utilization of resources and economic improvement, but there is little research on the nuclear auxiliary facilities, support systems, and structures of small reactors [4]. Containment is the most important structure of the reactor, the last safety barrier for nuclear safety, and one of the most important measures to prevent the spread of radioactive materials to the environment after the accident. Yu and Wang [5]comprehensively summarized the development situation of onshore reactor containment in various countries around the world in terms of the structural form of nuclear reactor containment. The containment of an onshore nuclear power plant is mainly designed in the form of prestressed steel reinforced concrete, which cannot meet the loading requirements in the marine environment in terms of weight, size, and design pressure. For example, the volume of the containment of a general onshore nuclear power plant is about 6×10^4 m^3. Regardless of the impact of material weight on the overall scheme, heavy prestressed concrete is used for the pressure and shielding with the design pressure of about 0.5 MPa [6]. It can be seen that the onshore nuclear power plant containment scheme has exceeded the general ship's main scale and displacement standards with poor heap suitability of ship.

Foreign countries have more experience in the use of military nuclear-powered ships, nuclear-powered merchant ships, or icebreakers, but there is scant public information on the design of the containment. In addition, due to its special application background, there are differences in the standards of design, refueling cycles, and other aspects, which have affected the selection of benchmark accidents, structural design, and system design of FNPP containment. Therefore, it is necessary to carry out the research on the design of FNPP containment so as to explore a better solution for the combination of ship reactor. By drawing on the design experience of mature nuclear-powered ships and onshore nuclear power plants, absorbing the codes and standards related to nuclear power, and adopting the idea of "design input-scheme design-structural verification", we propose a containment scheme and design method that are expected to be suitable for FNPP in this paper to provide a reference for engineering design.

1 Research on marine adaptability

The FNPP containment is one of the typical structures that need to be designed for marine adaptability. In addition to the adaptability problems of the FNPP containment in the aspects of space, weight, and containment pressure mentioned in the introduction, there are also problems of collision or impact at sea. Code of Safety for Nuclear Merchant Ships [Res. A.491 (X II)] issued by the International Maritime Organization in principle requires a distance of at least *B*/5 (*B* is the ship's width) from the containment to the outer shell of the hull, or has an equivalent collision protection structure approved by the regulatory authority[7], which requires certain safety protection measures on the side of the ship. Fig. 1 summarizes a flow method for marine adaptability analysis of FNPP containment, which can be used as a design reference. In terms of the length of the ship, the ship is required to have a high length-to-width ratio (*L*/*B*), usually greater than 5, to overcome platform sway (especially pitch). Therefore, the design of FNPP containment has a great influence on the ship's width and length. As for the weight, containment shielding is the main component of the entire platform weight, accounting for about 15% . Therefore, lighter and thinner shielding materials must be selected to reduce the shielding weight and ship width, which plays an important role in improving the economic performance of floating nuclear power plant. In addition, since the weight of the stacking section increases intensively, it is required to improve the total longitudinal strength of the ship and the bearing capacity of the dock foundation, which will lead to the increase in the weight of the ship structure and the rebuilding cost of the dock. Besides, due to the obvious space limitation, stringent requirements are put forward for the miniaturization of FNPP containment. As a result, the peak pressure of the containment is much higher than that of the onshore nuclear power plants in the case of design basis accidents. For example, the volume of the SAVANNAH nuclear-powered merchant containment is about 1 100 m^3, and the design pressure is about 1.28 MPa [8]. Therefore, certain pressure control measures need to be considered to meet the nuclear safety functional requirements of the containment. However, only the free volume of the containment can relieve the structural pressure requirements of the terrestrial nuclear power plants to a certain extent.

Therefore, for the guarantee of the nuclear safety function of the FNPP containment and improvement on the economic performance of the floating platform, the key is to control the volume and weight of the containment, reduce the pressure of the containment, and ensure the strength of the containment.

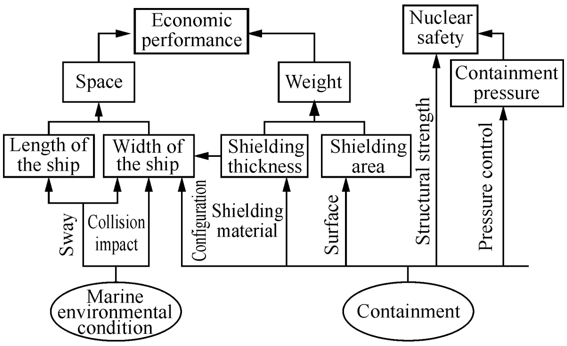

Fig.1 FNPP containment analysis flow

2 Design input

The space requirement of the containment is an important design input of the overall scheme. In addition to meeting the equipment layout, the containment space should also ensure that the pressure of the containment is lower than the structural strength and the latter is the main contradiction. Therefore, the research on the design input of the containment is mainly to solve the design basis accidents that affect the containment pressure and the related factors that inhibit the increase in containment pressure.

2.1 Determination of design basis accident

For pressurized water reactor containment, a big threat to the integrity of the containment design basis accident mainly includes a side of the loss of coolant accident (LOCA) and a secondary side main steam line break (MSLB). The mass energy release caused by these two types of accidents leads to the huge internal pressure of the containment in a relatively short period, posing a threat to the structural integrity of the containment [9]. For the distributed floating pressurized water reactor, the fracture of the cold section, the hot section, and the pump suction section of the main pipeline, as well as that of the main steam pipe, should be considered as the design basis accident of the containment in the design phase. Usually, the double end fracture of coolant main cold section is the most serious case in water loss accident.

The containment pressure and temperature response after the accident needs to be analyzed based on certain containment volume and suppression measures. After a quantitative analysis of multiple schemes, the overall design parameters met by the containment volume, pressure, and temperature parameters are finally selected, leaving a certain design margin [6].

2.2 Analysis of factors with suppression function

Factors that inhibit pressure and temperature rise include artificial suppression measures and heat absorption of containment structures and ancillary facilities. The suppression measures are used to deal with the peak pressure generated in the seconds before the containment accident after the design basis accident. In the late stage of the accident, the pressure and temperature of the containment can be reduced by kinetic residual heat extraction or other means.

Common suppression measures in onshore nuclear power plants include containment submergence, spray, and wet pool suppression [10]. The typical containment submergence is the large tank on top of the containment used by AP1000 nuclear power plant. The biggest disadvantage is that the tank is of big space and huge weight to adapt to the marine environment. The condensation effect of spray system is better than that of the submerged system, but its disadvantage is that dynamic spray depends on dynamic equipment, which is seriously affected by equipment and power reliability. The suppression of wet pool is derived from the boiling water reactor with the characteristics of immobility. The operation experience of the boiling water reactor shows a relatively perfect suppression effect of the wet pool which is convenient for arrangement [11]. For FNPP, the theoretical study shows that the suppression effect of wet pool is obvious, as described in Section 2.3.

However, there are some technical risks in using wet pool suppression technology for FNPP, which are mainly manifested in: 1) it lacks practical engineering experience; 2) the volume of the pressurized water tank is large. If the free volume of the containment has the function of reducing pressure, however, the weight burden of FNPP will be large after the pressurized water tank is filled with water. Therefore, this research scheme considers the wet pool suppression technology and carries out theoretical analysis and research to prepare for the later test verification. Whether the wet pool suppression technique is applicable to the floating nuclear power plant needs to be verified by further experiments.

2.3 Research on the containment accident of wet pool suppression

Free volume refers to the volume of the total volume of the containment after the removal of the structure and equipment coefficients. According to the principle of mass and energy release, the accident pressure of the containment can be preliminarily estimated [5]. Based on the design inputs such as the water loading capacity of the primary circuit, the pressure curves of different free volumes under LOCA accidents can be obtained, as shown in Fig. 2.

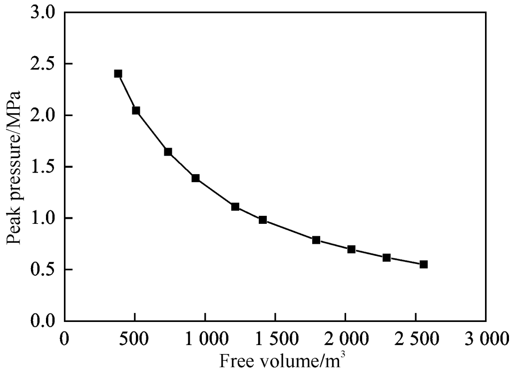

Fig.2 Peak pressure–free volume curve of the containment

The calculation shows that the free volume has a negative correlation with the containment pressure, and a smaller free volume leads to a more obvious increase in pressure. The free volume of the containment can be preliminarily determined according to the pressure target.

The technical scheme of wet pool suppression for FNPP has been introduced. The key to the design of this system is to determine the capacity and gas–water ratio of wet pool. If the gas–water ratio is overhigh, it is easy to lead to inadequate high temperature steam cooling. Otherwise, it will cause system startup or operation difficulties, indicating that too high or too low gas–water ratio will affect the suppression effect. After comparative study, this paper chooses 1∶1 gas–water ratio and carries out theoretical analysis on LOCA accident thermal response of different wet pool capacities under the free volume of 1 800 m^3, as shown in Fig. 3.

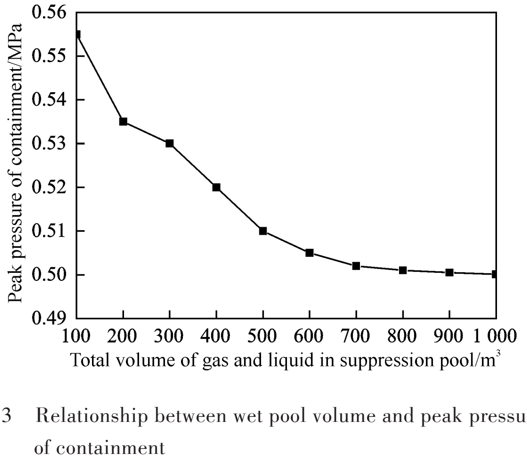

Fig.3 Relationship between wet pool volume and peak pressure of containment

2.4 Final design parameters

As can be seen from Fig. 3, when the volume of wet pool is within 500 m^3, the peak pressure takes a dive. At this volume, the peak pressure of the containment with or without wet pool suppression measures is shown in Fig. 4. The suppression effect of wet pool is obvious, and the peak pressure of the containment is reduced from 0.75 MPa to 0.51 MPa, a reduction of about 32% according to Fig. 4.

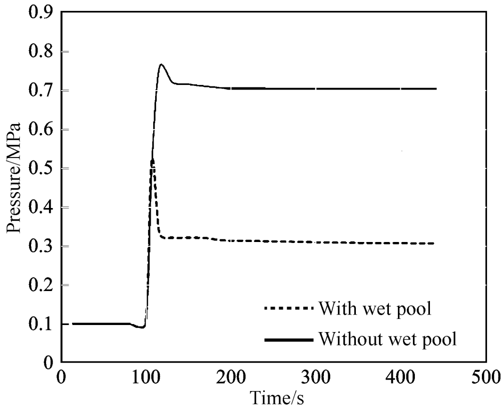

Fig.4 Comparison of pressure control effects with and without wet pool

Therefore, the free volume of 1 800 m^3 is the final design parameter of the containment, of which dry pool volume is 1 300 m^3 and wet pool volume is 500 m^3. The design pressure of the containment is 0.561 MPa after considering the design margin of 10%. This parameter will be used as an important input to the design of the containment structure. The structural strength of the containment should meet the requirements of various specified working conditions and load combinations. Relevant research and analysis are discussed in Chapter 4.

3 Research on spatial arrangement

3.1 Scheme overview

The FNPP containment is a kind of marine pressurized chamber. Considering that it will be affected by external loads such as collision, impact, and hull deformation in the marine environment, the outer wall of the containment should be weakly connected with the hull structure. In addition, it is also necessary to consider the installation process requirements of the shielding layer of the containment, the accessibility requirements of the structure inspection in service, and the local strength requirements of the perforations of the containment. The overall structure should be designed in a compact manner to improve the space utilization of the hull compartment.

The overall scheme characteristics of the FNPP recommended in this paper are shown in Fig. 5. The composite plate frame structure is strengthened on the outside of the pressure-resistant boundary of the containment, and the relief hole is set at the corresponding position of the plate. The strengthening method of the structure can make full use of the space of the containment. For example, the bottom and sides are weakly connected to the hull by means of relief holes. The bottom, top, side and rear can form empty compartments. After water injection, it not only has shielding effect, but also has containment cooling function, which can be used as cooling water source under accident conditions. The front part is an open structure, which is conducive to the arrangement of primary circuit and other system penetrators.

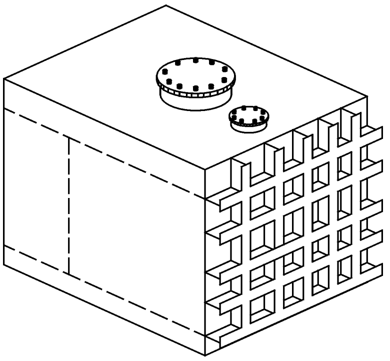

Fig. 5 Structural model FNPP containment

3.2 Configuration selection

According to the design experience of nuclear ships at sea, the FNPP containment has two schemes including cylinder and square, which have significant differences in the bearing capacity and space utilization. The overall space utilization rate of the square containment is high, and the multi-layer platform can be set inside. The story height between the platforms is not affected by the shell structure with a high space utilization rate of the equipment layout inside the shell. At the same time, the square structure fits well with the cabin of the hull with also a high space utilization rate of the hull. The latest nuclear-powered icebreaker and FNPP (KLT-40S) both adopt this scheme [12].

However, in terms of bearing capacity, the square containment is inferior to the circular containment. If a circular containment is used on a FNPP platform of the same main scale, the maximum free volume of the containment will decrease and the pressure will increase due to its low space utilization rate. After analysis and calculation, it is found that the pressure of the square containment is about 1/2 that of the circular containment, while the weight of the square containment is about twice that of the circular containment.

After adopting the measures of increasing the containment volume and pressure control, the pressure inside the containment can be effectively reduced, which is close to the level of onshore nuclear power plants, making the pressure and temperature of the square containment better adapt to the requirements of the design index of the existing equipment, and avoiding the problems caused by equipment re-identification or test in a wide range, which will not cause a significant decline.

After comprehensive analysis, it is concluded that FNPP is more suitable to adopt the square containment scheme.

3.3 Suppression of water cabin

In the design of floating nuclear power plant scheme, it is recommended to consider the use of the wet pool suppression technology of the pressurized water cabin. The arrangement and capacity of the pressurized water cabin of the FNPP containment are the keys to determining the overall scheme of the containment. The following principles should be followed:

1) integrated design with the containment;
2) within the pressure boundary;
3) arranged closer to the breach;
4) sufficient suppression capacity;
5) avoiding affecting primary circuit layout.

Therefore, this paper presents a wet pool arrangement scheme (Fig. 6) which consists of one main ballast cabin and two auxiliary ballast cabins, located in the rear and lower on both sides of the primary circuit system, respectively. The main and auxiliary ballast tanks are close to and around the main pipeline.

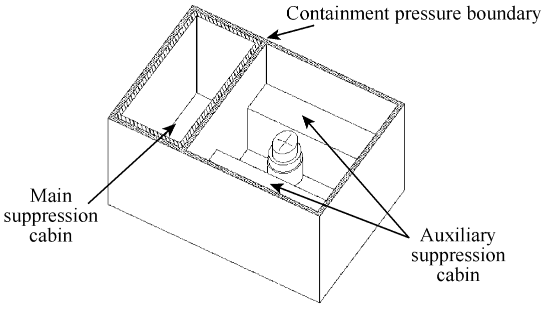

Fig. 6 FNPP wet-pool arrangement

3.4 Protective enclosure

Radioactive material inclusion is one of the main nuclear safety functions of containment. Code of Safety for Nuclear Merchant Ships requires four layers of security barriers for maritime nuclear power facilities, namely, nuclear fuel cladding, primary pressure boundary, containment, and protective enclosure [7]. The main function of a protective enclosure, a barrier surrounding the containment structure, is to prevent the unintended release of radioactive material and to limit its leakage. Therefore, the FNPP uses the containment protective enclosure, as shown in Fig. 7.

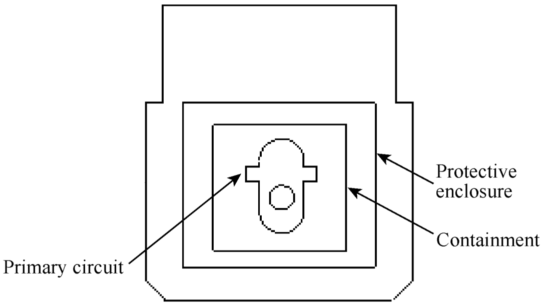

Fig.7 Configuration of FNPP containment protective enclosure

The inner containment is a primary structure, which is the containment boundary of pressure peak under the containment design basis accident and fission products of the inclusive water loss accident. Protective enclosure is a secondary structure, which is an integral part of the hull stacker structure, and should meet the requirement for certain leakage rate. For example, KLT-40S floating nuclear power plant requires a leakage rate of protective enclosure of up to 1% per day[12]. In addition, protective enclosure also has a good effect on fire prevention and collision prevention.

3.5 Radiation shield

According to the previous analysis on the space and weight limits of the containment, FNPP should consider the comprehensive utilization of shielding materials such as concrete, lead, cast iron, and water [12]. The thickness ratios of different equivalent shield materials are shown in Table 1. The shielding effect of lead is good with light weight and small size, but at a high cost. If other shielding materials are used alone, the weight and the main scale of the ship will increase and the comprehensive economic performance will be poor [13].

Therefore, it is advisable to adopt the policy of using lead as the main shielding material and other shielding materials as the auxiliary. The sandwich of the containment and the protective enclosure is used to install the shielded water cabin, and iron or concrete is used where the space allows to reduce the use of lead to increase the economic performance.

Table 1 Thickness ratios of radiation shield material

Material	Thickness ratio	Shielding object
Polyethylene ∶ boron polyethylene	1.3 ∶ 1	Neutron
Water ∶ boron polyethylene	2 ∶ 1	
Water ∶ lead	15 ∶ 1	Gamma
Iron ∶ lead	2 ∶ 1	
Concrete ∶ lead	5 ∶ 1	

4 Structural analysis and research

4.1 Item classification and standards

The safety classification of the containment structure should be determined in the first place for the strength analysis of the containment structure, which is the basis for ensuring the safety function of the containment. The codes for both onshore nuclear power plants and nuclear-powered ships stipulate that the containment is of nuclear safety level 2 [14-16]. In terms of the adoption of standards, the MC class in the NE subsection of volume 1 of ASME Code system is specifically designed for the steel containment and the design of the AP1000 nuclear power plant containment refers to this standard[14]. Therefore, the design of the FNPP containment also follows this standard.

4.2 Study on the working condition and load group

The containment structure shall meet the strength requirements of load combinations under different types of working conditions. In combination with the MC-level component design provisions in ASME Code[15], the containment loads are divided into several types of working conditions, such as A, B, C, and D. A detailed description is mentioned in the ASME Code, which will not be repeated here. The class-B working condition is the normal operating condition of the power plant and the load is not severe. Besides, the load strength is contained by other kinds of load, so it is not listed separately. With reference to the analysis model of onshore nuclear power plant containment, the FNPP will focus on marine environmental loads. In this paper, safety shut down wave load and extreme wave load are selected, so class-C working condition is divided into C1 and C2, replacing the earthquake load of onshore nuclear power plants. In addition, there are external loads caused by man-made events, such as ship collision, and helicopter collapse, which will be independently verified with reference to the onshore nuclear power plant model and not as the typical load conditions of the FNPP containment. Therefore, the containment design conditions and load group are shown in Table 2. Here, Ⅰ-Ⅺ represent respectively gravity, safety shutdown wave load, extreme wave load, test pressure, test temperature, working pressure, working temperature, design pressure, thermal response under the condition of the accident, thermal load under the condition of the accident, as well as the impact, swing, and reaction force of pipeline under accident conditions.

Table 2 Containment design conditions and load group

	Fixed load	Environmental load		Test load		Working load		Load of the design basis accident			Local load
Working condition	Ⅰ	Ⅱ	Ⅲ	Ⅳ	Ⅴ	Ⅵ	Ⅶ	Ⅷ	Ⅸ	Ⅹ	Ⅺ
Test	√			√	√						
A	√							√	√	√	
C1	√	√						√	√	√	
C2	√		√			√	√				
D	√	√						√	√	√	√

4.3 Study on stress intensity analysis

The ASME Code recommends two methods of strength limitation: analytical method and formula method. According to the structural characteristics of FNPP containment, there are components such as shell, plate support structure, structural discontinuity, and stress concentration area, so the method of analysis is suitable. The containment stress structure is divided into primary stress, secondary stress (Q), and peak stress (F). The primary stress is divided into total and partial film stress (P_{m} and P_{L}) and bending stress (P_{b}). The secondary stress is film stress plus bending stress.

For strength analysis, different stress types should be checked according to the stress characteristics of the containment components under different working conditions. According to the strength limits of the corresponding stress types in ASME Code, the finite element analysis program can be used to evaluate the strength of the containment structure, as shown in Table 3. S_{mc} is allowable stress; S_{ml} is the allowable stress intensity; S_{a} is the stress amplitude determined by the design fatigue curve.

Table 3 Structural stress limits of FNPP containment

Structural classification	Strength limit	Working condition
Hull	$P_{\mathrm{m}}<S_{\mathrm{mc}}$, $P_{\mathrm{L}}+P_{\mathrm{b}}<1.5S_{\mathrm{mc}}$	Test, A，C，D
Reinforcement structure	$P_{\mathrm{L}}+P_{\mathrm{b}}<1.5S_{\mathrm{mc}}$	Test, A，C，D
Structurally discontinuous area	$P_{\mathrm{L}}+P_{\mathrm{b}}+Q<3S_{\mathrm{ml}}$	A，C
Stress concentration area	$P_{\mathrm{L}}+P_{\mathrm{b}}+Q+F<3S_{\mathrm{a}}$	A，C

The influence of boundary conditions must also be considered in the stress intensity analysis, because the containment is weakly supported by the hull structure, which is helpful to improve the strength of the containment. Therefore, when analyzing the strength of the FNPP containment, the containment can be regarded as a structural model with an independent body and a base supported by the hull. Based on the load conditions group in Table 2 and according to the stress intensity limits in Table 3, the components such as the containment shell, skeleton, frame, and bracket are checked and calculated. Finally, it is determined that the containment structure strengthened by T-profile with a thickness of 38 mm and a height of 1 500 mm shall be adopted to meet the requirements of MC-level components in ASME Code. The weight of the containment structure is about 2 000 t, accounting for about 6.6% of the displacement of the floating platform. It can better adapt to the main scale requirements of the platform with the displacement of class 30 000 t and the heap power of 2 × 100 MW.

5 Conclusions

Based on the design of the FNPP containment and the adaptability of the containment to the marine environment, the space, weight, and pressure of the FNPP containment are proposed in this paper. In the design process, firstly, the design input of the FNPP containment is analyzed; the design basis accident is defined; the pressure level of the containment is demonstrated; the space requirements of the solidified containment are discussed. When designing a containment scheme, the influence of containment configuration, pressure control, safety barrier, and radiation shield on the overall performance of the containment should be emphasized. The design results must ensure the core functions contained by the radioactive material in the containment and verify the integrity of the containment structure under the combination of various accident conditions. Eventually, a method of structural strength analysis of FNPP of steel containment is presented, which can be used as a reference for designers.

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海洋环境条件下浮动堆安全壳设计

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摘　要:［**目的**］浮动堆经过在军用舰船上几十年的发展和运行经验积累,反应堆的安全性得到了很大提高,在民用领域的推广应用逐渐被认可,目前亟需解决反应堆装船的适配性问题。安全壳是浮动堆与船体结合的接口,是反应堆装船的船体舱室,其设计不仅要适应船舶的海洋环境条件,还要满足反应堆运行的核安全要求。［**方法**］首先,从浮动堆安全壳的适应性要求出发,分析安全壳压力与船舶主尺度和重量之间的主要矛盾关系,提出一种浮动堆安全壳分析设计流程。然后,参考陆上核电站和核动力舰船安全壳的特点,以及国外核动力船舶和民用核设施设计规范要求,从安全壳构型与压力控制维度的角度出发,提出一种方形双层抑压安全壳方案。［**结果**］对安全壳压力特性以及结构强度的分析显示,在设计基准事故工况下,安全壳结构安全,重量和空间指标可控,安全壳的船堆适配性较好。［**结论**］参考工程经验表明,基于该方案的浮动堆总体指标较好,可为工程人员设计提供参考。

关键词: 浮动堆; 安全壳; 海洋环境; 总体设计