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Design Thickness Variation in i-SMR Reactor Vessels: A Comparison of ASME BPVC Sec. III Subsections NB and NE

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1. Introduction

Small Modular Reactor (SMR) have emerged as next generation nuclear power technology, offering enhanced safety, economic efficiency, and flexibility. Unlike conventional large-scale reactors with concrete containment structures, innovative SMR (i-SMR) adopts the concept of a steel containment vessel (SCV), requiring specific design guidelines and technical considerations. The ASME Boiler and Pressure Vessel Code (BPVC) Section III [1] establishes requirements for materials, design, fabrication, installation, and inspection to ensure the safety and reliability of key nuclear components. This study investigates domestic and international cases of SCV applications, identifies the relevant ASME BPVC Section III subsections, and analyzes the rationale behind their application.

2. ASME BPVC Section III Subsection

2.1. Subsection NB (Class 1)

Subsection NB applies to major components of the Reactor Coolant Pressure Boundary (RCPB), such as pressure vessels, piping, and nozzles. It establishes design and fabrication criteria based on precise stress analysis, considering factors such as fatigue and crack growth under high-temperature and high-pressure conditions.

2.2. Subsection NE (Class MC)

In case of subsection NE, it is applied to metal containment vessels and metallic structures designed to prevent radioactive material leakage. It provides a design approach centered on external and internal pressure loads to prevent radioactive release during accidents.

3. Case studies of steel containment vessels

3.1. Domestic cases

Domestic nuclear power plants use reinforced concrete containment buildings with internal steel liners. Kori Unit 1 was classified under Subsection NC (Class II), while Kori Unit 2 applied Subsection NE. SMART100 follows Subsection CC (Code for Concrete Containments).

3.2. International case

The NuScale SMR steel containment vessel is fully submerged in a concrete water pool, utilizing natural convection and evaporation for heat removal. It is designed to withstand internal pressure loads. The vessel is classified as a reactor pressure vessel and has received NRC standard design approval (SDA) under subsection NB. [2] The i-SMR maintains a vacuum layer between the reactor pressure vessel and containment, reducing heat transfer, corrosion, and heat loss. It shares compact design and pressure resistance features with NuScale.

4. Comparison of stress limit and design thickness according to Subsection NB and NE

4.1. Stress Limits

ASME BPVC Section III defines stress criteria based on design conditions to ensure structural integrity**.** It ensures that the calculated stress intensity under operational limits satisfies the stress criteria, thereby guaranteeing structural safety. The types of stress criteria specified in the design code are summarized in Table I.

Table I Types of stress criteria and corresponding ASME BPVC section [3]

Stress criteria	Symbol	Code
Design stress intensity	S_m	Section II, Part D Table 2A, 2B, 4
Allowable stress intensity	S_{mc}	$S_{mc} = 1.1S$
Allowable stress	S	Section II, Part D Table 1A, 1B
Yield strength	S_y	Section II, Part D Table Y-1
Fatigue strength	S_a	Section III Mandatory Appendix I

For subsection NB (Class 1), the design stress limit is applied as the stress criterion (NB-3112.4). In contrast, for subsection NE (Class MC), the allowable stress intensity (S_{mc}) is used, calculated as 1.1 times the allowable stress (S). However, S_{mc} must not exceed 90% of the yield strength (S_y) specified in Section II (NE-3112.4).

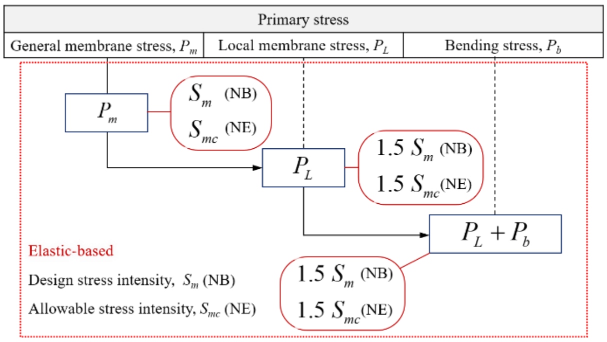

Fig. 1. Comparison of stress limits for Subsection NB and NE.

4.2. Comparison of minimum design thickness

The assumed specifications and stress limits of an i-SMR for comparing the minimum thickness based on the design codes applied to steel containment vessels summarized in Table 2.

Table 2 Minimum thickness of steel containment vessel for design criteria

Material	Inner radius [m]	Design pressure [MPa]	Design stress intensity [MPa]	Allowable stress [MPa]
SA508 Gr.3	4	4.1	184	174
XM-19			199	187

Minimum design thickness is calculated for each location using the following equations based on the applicable subsection. equation (1) and (2) are used to calculate the minimum design thickness for the cylindrical shell, while equation (3) and (4) are for the upper and under domes.

$$t = \frac{PR}{S_m - 0.5P} \quad \text{(NB-3324.1)} \qquad (1)$$

$$t = \frac{PR}{S - 0.6P} \quad \text{(NE-3324.3)} \qquad (2)$$

$$t = \frac{PR}{2S_m - P} \quad \text{(NB-3324.2)} \qquad (3)$$

$$t = \frac{PR}{2S - 0.2P} \quad \text{(NE-3324.4)} \qquad (4)$$

where t is design thickness; P is design pressure; R is inner radius; S_m is design stress intensity in Subsec. NB; S is allowable stress in Subsec. NE.

The upper and lower domes are assumed to intact spherical geometry. The calculated design thickness is summarized in Table 3.

The minimum design thickness under general stress conditions, excluding local stress concentrations, in found to be smaller when applying subsection NB criteria compared to subsection NE for steel containment structures. This is because the stress criteria in subsection NE allowing for a higher allowable stress compared to subsection NB.

Table 3 Minimum thickness of steel containment vessel for design criteria

Material	Location	Design thickness [mm]	Design criteria
SA508 Gr.3	Cylindrical shell	90	NB-3324.1
		96	NE-3324.3
	Upper dome	45	NB-3324.2
		47	NE-3324.4
XM-19	Lower dome	42	NB-3324.2
		44	NE-3324.4

5. Conclusion

This study analyzes the design codes and key issues related to steel containment vessels used in domestic and international nuclear power plants. It focuses on the design codes of Subsections NB and NE of ASME BPVC Section III. The stress criteria and evaluation requirements of each subsection are compared, and the minimum design thickness for a given design pressure is calculated and analyzed. The calculated design thickness is based on general membrane stress. Further analysis is required to considering critical weak locations such as penetrations and nozzles.

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REFERENCES

[1] ASME, ASME Boiler and Pressure Vessel Code, Division I, Section III, 2015.
[2] U. S. NRC, Design-Specific Review Standard 3.8.2 steel containment for NuScale design, Revision 0, 2016.
[3] ASME, ASME Boiler and Pressure Vessel Code, Division I, Section II, 2015.