

Review of Pre-Service and In-Service Inspection Issues for the Steel Containment Vessel of the Innovative Small Modular Reactor and Proposal of Inspection Methods

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1. Introduction

Small modular reactors are being developed worldwide as a means of reducing carbon emissions, replacing ageing large reactors and responding to a growing electricity demand. The innovative small modular reactor (i-SMR) under development in Korea adopts an integral primary system, a fully passive safety concept, boron-free operation and factory-based modular fabrication.

In this design the steel containment vessel (SCV) replaces the prestressed concrete containment building of a large light water reactor. The function of SCV, however, is far more than a leak-tight barrier. It encloses the integral reactor pressure vessel (RPV) and the heat exchangers of the passive containment cooling system (PCCS). The SCV is maintained under vacuum during normal operation in order to minimize heat loss, and it is designed for an internal pressure of the order of 5 MPa. It therefore possesses the characteristics of both a containment boundary and a Class 1 pressure-retaining component.

The domestic pre-service inspection (PSI) and in-service inspection (ISI) framework, comprising Article 16 of the Nuclear Safety Act, Articles 41 and 63 of the Regulation on Technical Standards for Nuclear Reactor Facilities, NSSC Notice No. 2018-5 on containment leakage testing and the KEPIC MI series [1-4], was established on the premise of a large, low-pressure concrete containment building having a large free volume. Direct application of these requirements to the SCV is consequently not straightforward.

This paper examines the applicability of those requirements to the SCV, identifies the resulting technical limitations and proposes inspection items and methods tailored to the vessel.

2. Design Characteristics and Applicable Codes

2.1 Design characteristics

Three features govern the inspection problem. The first is structural compactness: the steam generator, pressurizer and coolant circulation devices are integrated within the RPV, and the PCCS heat exchangers are installed in the annulus between the RPV and the SCV. The second is the operating environment: the SCV interior being held at a vacuum during normal operation. The third is modularity: the entire module being fabricated and assembled in a factory and transported to the site for installation. A comparison with the NuScale

Power Module, whose containment concept is closely similar, is given in Table I.

Table I: Comparison of the NuScale Power Module and the i-SMR

Item	NuScale Power Module	i-SMR
Reactor type	Integral PWR	Integral PWR
Output per module	77 MWe	170 MWe
Plant output	924 MWe (12 modules)	680 MWe (4 modules)
Design life	60 years	80 years
Steam generator	Helical coil	Helical coil
Containment	Steel, vacuum during operation	Steel, vacuum during operation
Cooling concept	Module submerged in pool	Dry type with PCCS

2.2 Safety classification and applicable codes

The SCV is classified as Safety Class 1 and Seismic Category I. Under KEPIC MNA it would ordinarily be an MC (metal containment) component; However, in order to permit a detailed fatigue and stress evaluation under the high temperature and pressure environment, the shell and heads are constructed to KEPIC MNB and the support skirt to KEPIC MNF, as allowed in the special requirement of MNA 2230. Overpressure protection follows MNE 7000 because the vessel nevertheless performs a containment function. This dual character is the origin of most of the issues discussed below. The principal regions of the vessel and the corresponding KEPIC MIB examination categories are shown in Fig. 1.

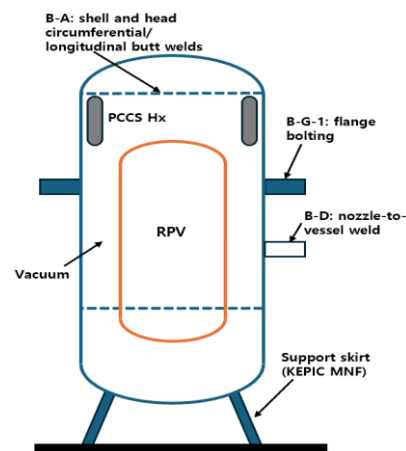


Fig. 1. Principal regions of the i-SMR steel containment vessel and the corresponding KEPIC MIB examination categories.

3. Pre-Service Inspection

3.1 Current practice and applicable requirements

For a concrete containment, PSI consists of construction-stage inspections (concrete placement, reinforcement and post-tensioning tendons, liner plate weld examination), a structural integrity test in which the building is pressurized in stages to 1.15 times the design pressure while radial/vertical displacement, strain and crack behavior are monitored, and an integrated leak rate test (ILRT) performed below the design pressure with an acceptance limit of 75 % of the allowable leakage rate, combined with local leak rate tests.

Because the SCV is fabricated and assembled in a factory, the greater part of its PSI is subject to shop inspection under KEPIC MNB and MNF. Plates and forgings are examined by UT(Ultrasonic Test) together with MT(Magnetic Particle Test) or PT(Penetration Test) in accordance with MNB 2000; Category A through D pressure-retaining welds are examined by RT(Radiographic Test) or UT and by surface examination in accordance with KEPIC MEN; a hydrostatic test using water as the test medium is required, followed by a leak examination held at the greater of the design pressure and three quarters of the test pressure in accordance with MNB 6224. MIB 2200 further requires pre-service examination of every Class 1 pressure-retaining weld, which establishes the baseline against which subsequent ISI results are compared. Supports are examined under MNF 2000 and MNF 5000.

3.2 Limitations of the current requirements

Once the RPV and the internal components have been installed, filling the SCV with water for the test is impracticable, and a pneumatic test at a design pressure of about 5 MPa carries an unacceptable stored-energy hazard. The ILRT requirement of NSSC Notice No. 2018-5 presumes a large free volume and a comparatively low test pressure, neither of which applies to the SCV; for a closely similar vessel, NuScale obtained NRC approval of an exemption from the Type A test [7,8]. Local leak rate testing remains applicable in principle, but whether penetrations and isolation valves can be pressurized to the required reference test pressure has still to be confirmed, and design modification of the affected components may be necessary. Finally, because much of the inspection is performed in the shop, a defined route for transferring factory records to and reconciling them with the post-installation site inspection is required.

4. In-Service Inspection

4.1 Current practice and applicable requirements

For concrete containment, KEPIC MIE governs the metal containment and liner, and KEPIC MIL governs the concrete structure and the post-tensioning system, both calling for a system pressure test. The examinations required by MIE are essentially visual, supplemented by ultrasonic thickness measurement.

Although the SCV falls within the MC class by MNA classification, examinations of this kind are not commensurate with its duty. The vessel operates at high pressure, supports the RPV and control rod drive mechanism, and contains many welds between the heads and the shell courses. Since it is designed and fabricated to MNB and MNF, its in-service examination is more appropriately governed by KEPIC MIB, under which the relevant categories are B-A, B-D and B-G-1 as identified in Fig. 1.

4.2 Limitations of the current requirements

The system leakage test of MIA 5000 and MIB 5000 presumes pressurization of the component at a pressure not less than the pressure corresponding to 100% rated reactor power or maximum pressure under design basis accident conditions. With the RPV and the PCCS heat exchangers installed, a hydrostatic test or pneumatic test of the SCV at these pressure levels may not be feasible. Therefore, further discussion is required to determine a realistic and reasonable test pressure. Accessibility is a second constraint: the congested annulus leaves little room to manipulate conventional examination equipment, and the high radiation environment restricts examiners' direct access.

5. Proposed Inspection Approach

The approach proposed here, summarized in Fig. 2 and Table II, takes KEPIC MIB rather than MIE as the governing basis and tailors it to the design characteristics of the SCV.

5.1 Non-destructive examination

Categories B-A, B-D, and B-G-1 are examined volumetrically and by surface methods based on MIB. Because direct access is restricted, remotely operated ultrasonic manipulators and compact crawler-type inspection robots should be applied, and phased array ultrasonic testing should be used at nozzles and other geometrically complex regions to improve detection reliability and to reduce occupational dose. Personnel and equipment are qualified under KEPIC MIZ Appendix VIII, whose performance demonstration should be extended to cover examination from within a confined space.

5.2 Leakage integrity

A three-stage strategy is proposed in place of the single design-pressure ILRT. In the shop, the hydrostatic test is performed on the SCV before assembly with the RPV; where the assembly sequence does not allow this, a full-scale mock-up vessel identical to the production item may be tested instead. High-sensitivity helium leak testing, in which helium is sprayed locally on the outer surface while the interior is held under vacuum, allows rapid determination of both the location and magnitude of any leak.

During operation, the vacuum maintained inside the SCV makes any breach of the containment boundary

immediately apparent as a change in the internal pressure, so that continuous vacuum monitoring provides continuous leakage surveillance. The NRC accepted an equivalent argument for NuScale, where continuous monitoring of leakage into the containment was credited in lieu of the VT-2 examination of ASME Section XI, IWA-5241(c) [7,9]. Type B and Type C local leak rate tests continue to be performed on penetration flanges and isolation valves at each refueling outage.

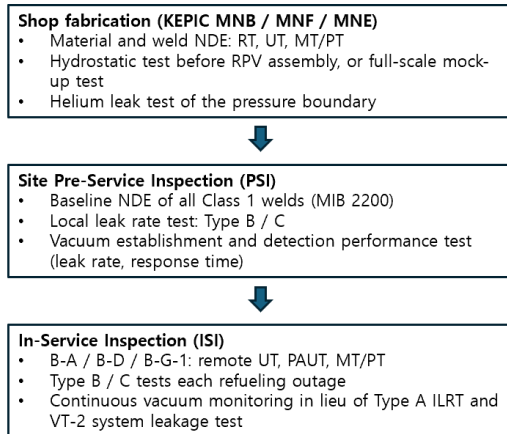


Fig. 2. Proposed three-stage inspection and leakage integrity framework for the steel containment vessel.

5.3 Regulatory considerations

For the proposed scheme to be accepted, the detection performance of the vacuum monitoring system, expressed as a minimum detectable leakage rate and a response time, must be quantified and adopted as a pre-service test acceptance criterion; NuScale verified the corresponding function at a level of approximately 1 gpm within one hour in its pre-operational test program [9]. In the longer term, the acceptance by the NRC of PSI and ISI programs based on ASME Section XI, Division 2 (Reliability and Integrity Management) for advanced reactor designs, through Regulatory Guide 1.246 [5,6], suggests that a risk-informed, performance-based inspection framework should also be considered for the i-SMR.

Table II: Proposed inspection items and methods

Region / item	Method
Shell and head butt welds (B-A)	UT (remote, PAUT) and MT / PT
Nozzle-to-vessel welds (B-D)	PAUT
Flange bolting (B-G-1)	Surface and volumetric
Outer surface and coating (if any)	VT (remote camera)
Penetrations, isolation valves	Type B / C local leak test
Containment boundary leakage	Continuous vacuum monitoring

6. Conclusions

The steel containment vessel of the i-SMR performs a containment function and acts as a Class 1 pressure-retaining component as well. It is accordingly more appropriate to apply KEPIC MIB, which requires non-destructive examination of the pressure boundary welds,

than KEPIC MIE, which primarily focuses on visual and surface examinations. MIB was nevertheless written for the reactor coolant pressure boundary of a conventional pressurized water reactor, and its examination items, methods and intervals must be adjusted to reflect vacuum operation, a high design pressure and restricted internal access.

The high design pressure and the density of internal equipment make a hydrostatic test of the assembled vessel and a design-pressure-based integrated leak rate test impracticable, so the reasonable and practical test pressure should be discussed further. A hydrostatic test performed before assembly with the RPV or on a full-scale mock-up, high-sensitivity helium leak testing, local leak rate testing of penetrations and isolation valves, and continuous vacuum monitoring together may constitute a technically defensible alternative. Recognizing continuous vacuum monitoring as a formal means of in-service leakage surveillance, quantifying its detection performance as an acceptance criterion, and revising the relevant notices and inspection guides accordingly may be part of the required regulatory actions.

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