Consideration of GWR Technique Adaptation for Pressurizer Level Measurement in i-SMR

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ABSTRACT

This study explores the application of Guided Wave Radar (GWR) technology for measuring the pressurizer level in the Innovative Small Modular Reactor (i-SMR), aimed at maximizing safety and operational efficiency.

Unlike conventional large-scale nuclear power plants, the i-SMR features an integral reactor structure that necessitates minimizing lateral penetrating piping. In turn, the GWR method, which allows for minimally invasive measurement through the top flange, is considered a promising alternative. GWR offers superior accuracy by directly measuring the liquid surface, overcoming the limitations of differential pressure-type gauges sensitive to coolant density changes. Furthermore, it enables continuous measurement—unlike Heated Junction Thermocouples (HJTC)—and is less susceptible to signal interference compared to ultrasonic methods.

The primary design focus is ensuring survivability under extreme conditions. To maintain hermetic sealing under high temperatures (300°C) and high pressures (200 bar), the integrity of the probe module and internal sealing is critical. Verification will be conducted through empirical testing using a dedicated high-temperature, high-pressure chamber. Additionally, since the transmitter is located far from high-radiation areas, specialized Mineral Insulated (MI) cables, advanced connector technologies, and high-precision signal processing algorithms are required to detect microvolt-level echo signals despite signal attenuation and loss.

Key performance requirements include an accuracy and repeatability within 10mm over an 8m measurement range, with a response time of less than 2 seconds. To compensate for level errors caused by dielectric constant fluctuations in the two-phase (water-steam) environment, a Time Domain Reflectometry (TDR) based reference measurement technique is applied. Lastly, for ease of maintenance, a weight is attached to the bottom of the probe, and a funnel-shaped supporter is designed on the surge plate to facilitate installation. A self-diagnostic function is also integrated to monitor sensor anomalies.

The design requirements for GWR derived from this study are expected to serve as core technologies to enhance the reliability of the integrated instrumentation and control system of the i-SMR.

Keywords: *i-SMR, GWR, TDR, Pressurizer Level, Survivability*

1 INTRODUCTION

The pressurizer level instrumentation provides essential input for primary coolant inventory control and reactor protection in pressurized water reactors (PWRs), including small modular reactors (SMRs). In the integral i-SMR, the reactor coolant system and pressurizer are housed within a single pressure vessel, severely constraining lateral penetrations. Conventional differential-pressure (DP) instruments require multiple nozzles and show high sensitivity to coolant density, temperature, and two-phase conditions, compromising accuracy during transients. Alternative technologies such as heated junction thermocouples (HJTCs) and ultrasonic gauges suffer from discontinuous indication, flow-induced noise, or strong steam-quality dependence.

This work explores guided wave radar (GWR) technology, based on time-domain reflectometry (TDR), as a minimally invasive, top-mounted solution for i-SMR pressurizer level measurement. GWR has been widely adopted in process industries for storage tanks, boilers, and spent fuel pools, providing direct, continuous measurements with high accuracy under extreme conditions. Unlike free-space radar, GWR confines high-frequency pulses along a probe waveguide, making it largely immune to foam, vapor, or internal structures.

When the pulse encounters an impedance discontinuity—such as the steam-water interface—reflected energy returns to the transmitter, and time-of-flight yields the distance. Being time-based rather than pressure-based, GWR is inherently insensitive to fluid density variations and well-suited for large temperature gradients or two-phase environments. The waveguide configuration also permits locating sensitive electronics outside the high-radiation zone via mineral-insulated (MI) cables, enhancing maintainability and survivability.

The objective is to develop a Class 1E, safety-related GWR system capable of withstanding i-SMR pressurizer conditions (≤300 °C, 20 MPa, two-phase) over 80 years while maintaining ±50 mm accuracy across a ~9–10 m span. This paper addresses key design elements for signal integrity, penetration and safety-class requirements, installation constraints, and the planned qualification program.

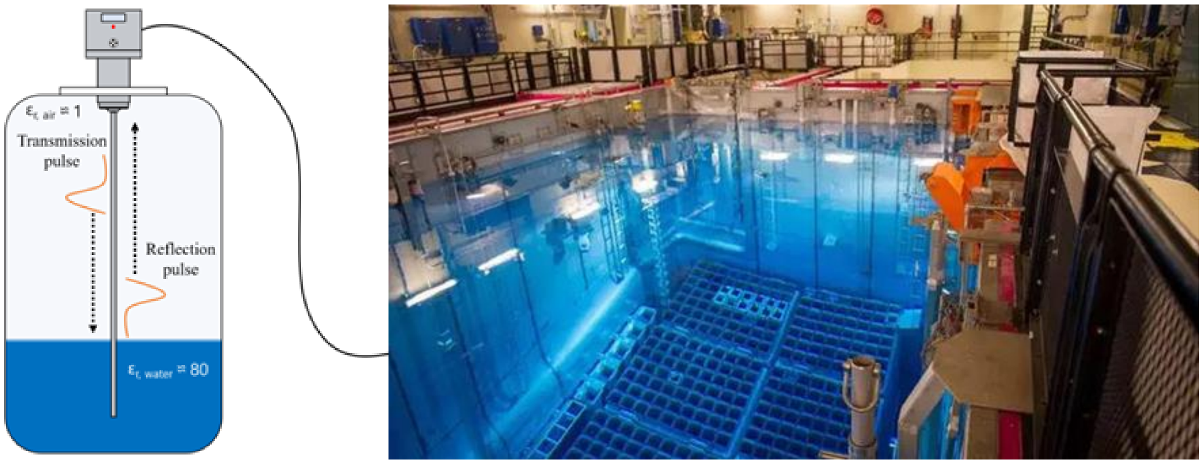

Figure 1: Spent fuel pool using GWR based on TDR

2 SYSTEM REQUIREMENTS AND MEASUREMENT CONCEPT

For the i-SMR application, the pressurizer level measurement is classified as a safety-related function providing input to the reactor protection system for high and low pressurizer level trips. Consequently, the developed instrument is assigned electrical safety class 1E and seismic category I, which implies that the complete set of measurement including the in-vessel probe, probe module, MI cables, transmitter, and associated software—must be designed, qualified, and maintained in accordance with safety requirements over the plant lifetime.

From an environmental standpoint, the instrument is exposed at harsh conditions in the containment. Inside the containment, the probe and a portion of the cable are subjected to normal operating temperatures up to 300 °C and pressures up to 20 MPa, with relative humidity of 100 %, and to postulated accident conditions up to 350 °C and steam-saturated atmospheres. The accumulated radiation dose in this region is expected on the order of MGy over 80 years, dominated by neutron and gamma fields, which strongly constrains the selection of materials for the probe module, seals, and cable insulation. Outside the containment, in the field instrument room, the transmitter experiences a much milder environment, with ambient temperatures between 10 and 40 °C and cumulative gamma doses under 100 Gy, but must meet electromagnetic compatibility and seismic resistance requirements.

The functional measurement range is dictated by the geometry of the integral pressurizer. The lower bound is defined near the surge plate region, while the upper bound is in the steam space close to the top head, yielding an active level span of roughly 0–9.5 m with a small dead zone below the mounting flange for structural reasons. Within this span, the design goal is to achieve a combined uncertainty within approximately ±50 mm, including systematic and random components, at a confidence level compatible with safety analysis assumptions. The dynamic response time, defined as the time required for the output to reach 90 % of its final value after a step level change, is targeted at less than 2 s so that both protection systems and operators can correctly interpret the plant state during rapid level transients.

To interface seamlessly with the i-SMR I&C architecture, the transmitter adopts a two-wire, loop-powered 4–20 mA analogue output, optionally superimposed with a digital protocol such as HART, with configurable lower and upper range values and built-in status and diagnostic signal. Functionally, the sensing and signal-processing portions of the system are spatially separated: the in-vessel probe and penetration assembly form a passive waveguide structure in the harsh environment, while the active electronics reside in a more benign location and communicate with the probe via MI cables. This separation reduces electronic exposure to harsh conditions, simplifies maintenance during outages, and facilitates future transmitter or firmware upgrades without modifying the pressure boundary.

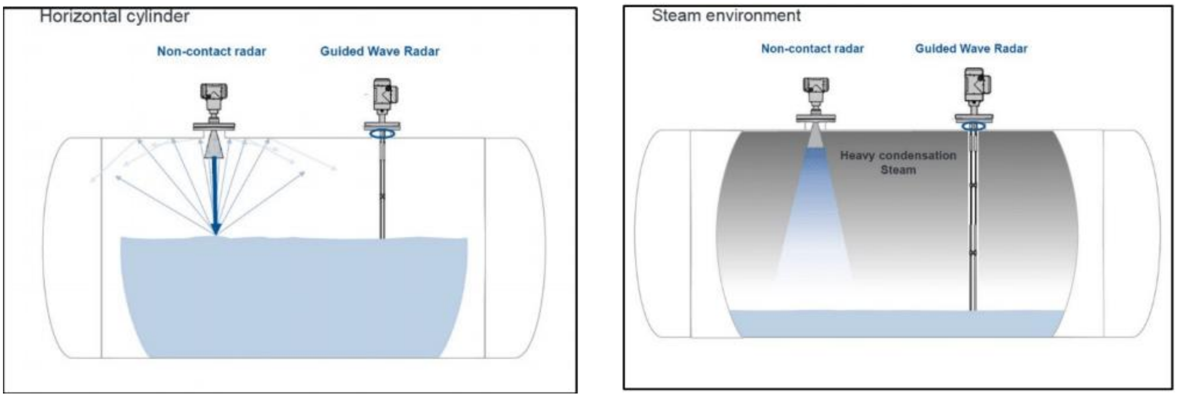

Figure 2: Non -contact radar vs GWR in horizontal tank (left) and in steam environment (right)

3 GWR-BASED PRESSURIZER LEVEL INSTRUMENT FOR I-SMR

3.1 Measurement Principle and Rationale for GWR

The selected instrument employs GWR using TDR along a probe installed vertically inside the pressurizer. A high-frequency electromagnetic pulse is injected into the probe, which behaves as a waveguide; at the interface between steam and water, the large permittivity contrast creates a sharp change in impedance, generating a reflected signal whose time-of-flight is proportional to the distance to the interface. Because the interface is detected directly, the method is only weakly affected by changes in fluid density, conductivity, or temperature, and is robust in two-phase conditions.

Compared with conventional float, differential-pressure, capacitive, ultrasonic, or optical instruments, the GWR/TDR approach avoids many material-degradation and sensitivity issues that become critical in an integral i-SMR pressurizer. Mechanical floats and acoustic transducers can suffer from rapid wear, fouling, or drift in harsh environments; capacitive and differential-pressure instruments are strongly influenced by fluid properties and temperature gradients; optical and ultrasonic devices can be limited by steam quality, bubbles, or internal structures. GWR mitigates these limitations and allows the electronic transmitter to be located outside the high-radiation region, connected through MI cables.

3.2 DESIGN BASIS ASSUMPTIONS

At the time of development, detailed upper-level plant design requirements were not fully established, so key design inputs for the pressurizer level instrument were conservatively derived from operating PWR experience and U.S. new-plant safety analysis reports. Assumed inputs include representative containment environmental envelopes, safety function categorization (protection, monitoring, post-accident monitoring), required response time and range, accuracy targets, routing and penetration concepts, and constraints related to refueling and head removal. These assumptions will be refined as the i-SMR standard design requirements are finalized.

3.3 SAFETY CLASSIFICATION AND FUNCTIONAL ROLE

The GWR pressurizer level instrument is classified as Class 1E, seismic Category I, with embedded software designed in accordance with the highest applicable safety integrity level. Its primary function is to provide continuous level information for inventory control of the reactor coolant system and to generate high- and low-pressurizer-level trip signals for the RPS, thereby preventing conditions such as heater exposure or overfill and supporting actuation of engineered safety features as required by the plant safety analysis.

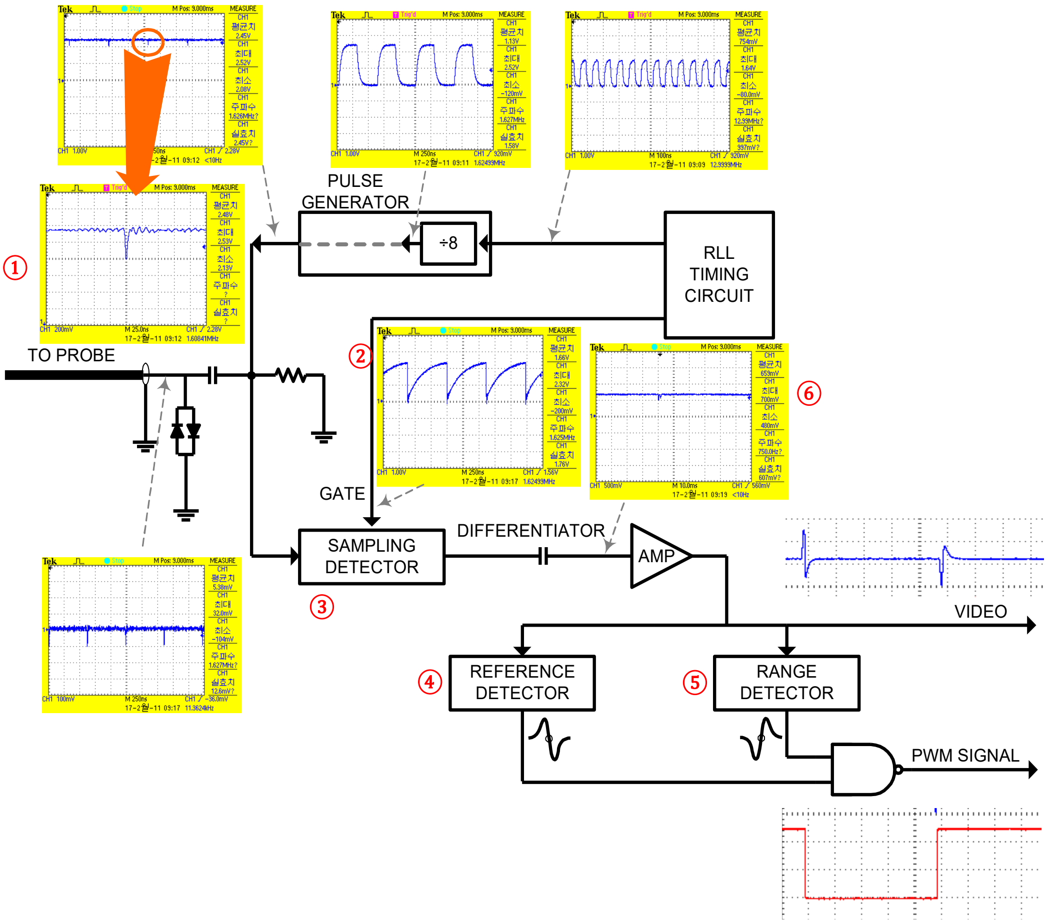

Figure 3: GWR Transmitter circuit logic and signal flow for TDR signal processing

4 KEY DESIGN ELEMENTS: SIGNAL INTEGRITY AND PRECISION

4.1 TDR Signal Characteristics and Challenges

A central challenge in the GWR implementation is to preserve the integrity of very low-level TDR signals, often reduced to the millivolt range after propagation and reflection, along a long probe and cable path in a noisy, thermally stressed environment. Attenuation, dispersion, and external electromagnetic interference can distort the waveform and obscure the level-interface reflection if not carefully controlled. The design therefore combines hardware measures for impedance control and noise mitigation with advanced signal-processing algorithms.

4.2 Probe and Front-End Hardware Design

On the hardware side, the probe and front-end are designed to maintain a controlled characteristic impedance (e.g., 75 Ω) from the TDR transmitter, through the probe guide, to the sensing section, thereby minimizing spurious reflections and standing waves. A flexible wire-type probe is chosen instead of a long rigid coaxial rod to satisfy seismic and mechanical constraints while still maintaining acceptable electromagnetic performance; multi-stage sealing and electrical insulation between the central conductor and the outer metallic sheath protect against moisture ingress and corrosion products that could degrade signal quality.

The probe module forms part of the reactor coolant pressure boundary and must withstand high pressure, temperature, and radiation over the plant life. The design uses multi-stage O-ring sealing, carefully controlled gaps between the metallic parts and polymer fillers, and materials compatible with the expected thermal and radiation environment. The geometry also limits flow-induced vibration and avoids contact with internal structures that could cause wear or signal artefacts.

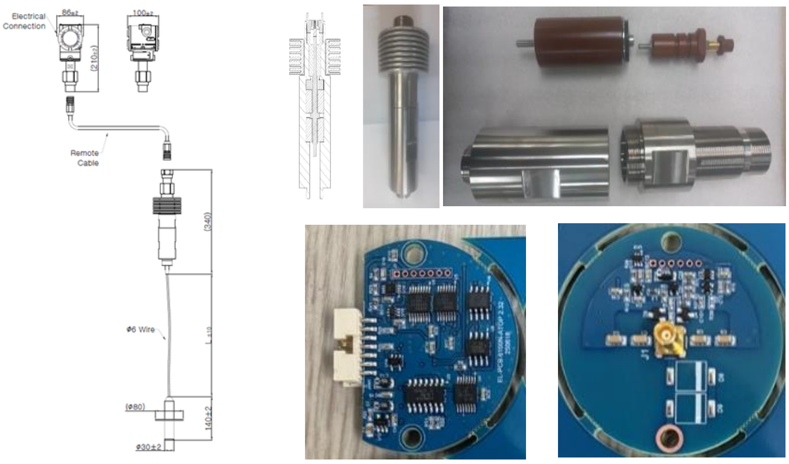

Figure 4: GWR probe module configuration and its prototype with HW circuit

4.3 Signal Processing and Diagnostic Algorithms

The TDR waveform acquired by the transmitter is subject to multi-stage digital processing to improve signal-to-noise ratio and robustly identify the level-interface reflection. Pre-processing functions include moving-average or median filtering, Kalman filtering, wavelet-based denoising, and ensemble averaging, which suppress random noise and high-frequency electromagnetic disturbances while preserving the sharp transitions associated with impedance discontinuities.

After pre-processing, reflection-detection algorithms such as tangent-based edge detection, bounded mean oscillation, or adaptive thresholding are applied to determine the precise location of the steam–water interface in the time domain. These algorithms are designed to cope with varying noise conditions, changing signal amplitudes due to temperature or dielectric variations, and slowly evolving baseline shifts. Embedded diagnostic functions monitor waveform quality and internal consistency to detect potential sensor degradation or failure modes, thereby supporting condition-based maintenance.

The transmitter is implemented as a low-power, two-wire, 4–20 mA loop-powered device, so all TDR generation, signal processing, self-diagnostics, and communication must be accomplished within the limited current budget of the loop. This places a premium on efficient hardware architectures and optimized firmware.

5 PENETRATION DESIGN AND SAFETY-CLASS CONSIDERATIONS

5.1 Reactor Pressure Boundary Interface

The sensor probe assembly is installed through a dedicated nozzle in the upper head region of the integral vessel so that the active probe length covers the full normal operating level range. The probe mounting and sealing arrangement forms part of the reactor coolant pressure boundary and must therefore satisfy applicable Class 1 mechanical design, pressure-boundary integrity, fatigue, and seismic requirements. The head-nozzle interface and probe support must tolerate differential thermal expansion, flow-induced vibration, and mechanical loads during normal operation and transients without compromising structural integrity or causing unwanted movement of the probe.

5.2 Containment Penetration, MI Cables, and Connectors

From the pressurizer head, the level-instrument cable is routed through the pressure boundary via a high-pressure, high-temperature connector, then through a containment electrical penetration assembly (EPA), and finally to a mild-environment cabinet. For a Class 1E, seismic Category I instrument, the following aspects are critical even if not all details are specified in the original development document.

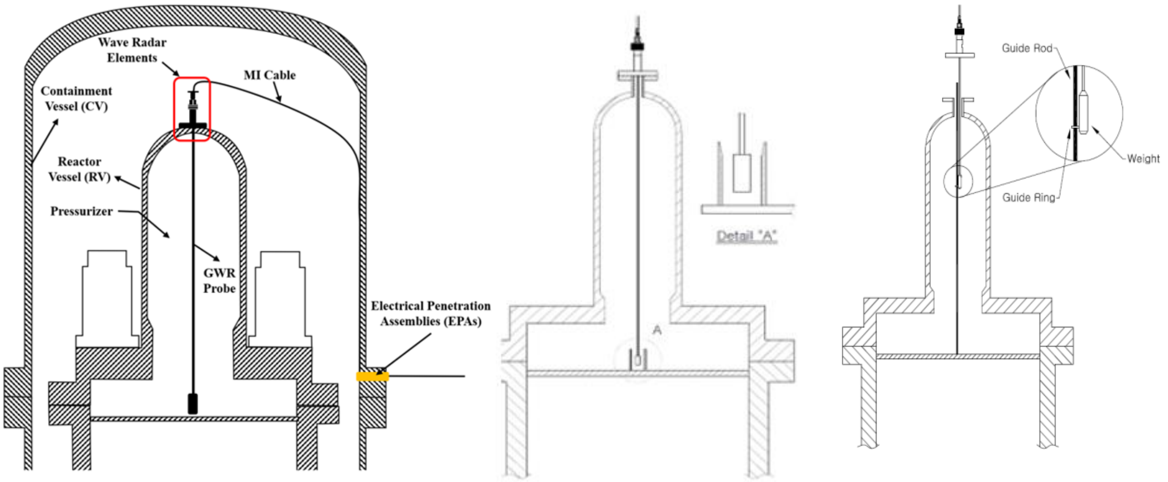

Figure 5: GWR-MI cable routing plan and methods not to let wire swing

First, the use of radiation-resistant mineral-insulated (MI) or qualified cables for the in-containment portion, with documented performance under temperature, pressure, humidity, and radiation conditions for the plant lifetime. Second, hermetic feedthroughs at both the pressure boundary and containment boundary that maintain leak-tightness under normal and design-basis accident conditions, including LOCA and seismic events. Third, Adequate EMI/EMC protection through shielding, grounding, segregation of safety and non-safety circuits, and routing practices that prevent common-cause failures. The last, the connectors designed for repeated mating/de-mating, with environmental sealing and materials compatible with the containment environment.

Because the GWR system is safety-related, the complete instrument loop—including probe, MI cables, connectors, and transmitter—must be qualified in accordance with relevant environmental and seismic qualification standards and regulatory guides (e.g., IEEE 323/344, IEEE 603, NRC regulatory guides), although detailed citations are omitted here for brevity.

6 INSTALLATION AND MAINTAINABILITY CONSTRAINTS

The integral configuration of the i-SMR imposes strict constraints on physical access, routing space, and outage maintenance strategies for in-vessel instruments. The GWR probe must be vertically installed through the dedicated head nozzle to cover the required level span, with adequate support to prevent excessive deflection or vibration while respecting the minimum bending radius of the flexible probe and avoiding twisting or damage to insulating components during installation. The routing of the cable from the head to the containment penetration must obey predefined paths that minimize exposure to high-temperature regions, avoid interference with other equipment, and maintain separation between redundant safety trains.

Maintenance and calibration are expected to be performed primarily during refuelling outages. Sufficient space and handling provisions must be available to remove and re-install the long flexible probe assembly without exceeding allowable bending limits or damaging surfaces. Quick-disconnect, qualified connectors at the head nozzle and at accessible junction points can facilitate probe replacement without invasive work on the pressure boundary. Embedded self-diagnostic functions in the transmitter—monitoring waveform quality, reflection signatures, and internal status—are planned to support early detection of degradation and to optimize maintenance intervals.

AUTROL

GWR 수위계 내압 자체시험 보고서

Report No (보고서번호) : PTR-10-2411-001

PAGE (페이지) : 1 OF 1

Project Name (공사명) : iSMR

Customer (고객) : -

Procedure No. (절차서번호) : -

Traveller No. (작업공정표 번호) : -

Test Equipment (사용장비)

Name	Manufacturer	Model No.	Cal. Date	Cal. Due Date
Pressure Gauge	Autrol	APT3200	2023.09.13	2024.09.12
Air Compressor	HANSHIN	NH-10	N/A	N/A
Air Regulator	TPC	TAW3000	N/A	N/A
Air driven Liquid Pump	Haskel	MS-220	N/A	N/A
Valve (Input, Drain)	BuTech	DHP4F	N/A	N/A

Tag No. (식별번호)	Shell				Pressure Test Result (압력시험 결과)
	Test Type (시험종류)	Pressure standard (압력기준)	Test Pressure (시험압력)	Test Time (시험시간)	
	-	bar	bar	Min	
PMODULE1	■ Water (물) ☐ Air (공기)	150	173	1	■ Accept ☐ Reject
	■ Water (물) ☐ Air (공기)	250	251	1	■ Accept ☐ Reject

첨부 : 수압시험 절차서

Ambient Temp. & Hum. : 22 ℃ & 54 % R.H

Action Taken In Connection With Any Deviations : N/A

Remark : N/A

Tested By		Inspection By		Evaluated By	
장광구	2024.11.12	송기호	2020.11.12	강철진	2024.11.12
Name	Date	Name	Date	Name	Date

Figure 6: GWR 8m high water tank test and EMI test report

7 FUTURE WORK AND QUALIFICATION PROGRAM

Future work will focus on comprehensive qualification of the GWR pressurizer level instrument for i-SMR application. Environmental qualification will demonstrate that the probe, MI cables, connectors, and electronics maintain their safety function under normal operation, anticipated operational occurrences, and design-basis accident conditions, including bounding temperature, pressure, humidity, and radiation profiles in the containment. Seismic qualification will verify that the probe assembly, supports, penetrations, and associated equipment preserve structural integrity and functional performance under operating-basis and safe-shutdown earthquakes, typically by shake-table testing and analysis in accordance with applicable standards.

In parallel, dedicated thermal-hydraulic test loops will be used to validate measurement accuracy, response time, and stability under realistic pressurizer conditions, including two-phase behaviour, surge-like transients, spray and heater operation, and possible thermal stratification. These tests will be complemented by EMC testing and rigorous software verification and validation of the embedded algorithms, following nuclear digital-I&C standards, to demonstrate that the GWR-based pressurizer level instrument can reliably support safety-related functions throughout the i-SMR lifetime. The resulting design and qualification framework is expected to contribute to a more reliable integrated instrumentation and control system for the i-SMR.

8 CONCLUSION

This study has presented the design concept and requirements for a GWR pressurizer level measurement system tailored to the i-SMR integral reactor configuration. By employing time-domain reflectometry along a top-mounted probe, the GWR approach minimizes penetration requirements, avoids the density-sensitivity limitations of differential-pressure instruments, and enables continuous, high-accuracy level measurement under the demanding two-phase, high-temperature, and high-pressure conditions of the i-SMR pressurizer.

Key design elements have been identified to ensure signal integrity, including controlled-impedance hardware, flexible probe construction for seismic robustness, multi-stage signal processing with advanced reflection-detection algorithms, and low-power loop-powered transmitter architecture. Careful attention to pressure-boundary and containment penetration design, use of radiation-resistant MI cables and qualified connectors, and compliance with Class 1E safety and seismic requirements position the system to meet nuclear safety standards over an 80-year plant lifetime.

Installation and maintainability considerations have been addressed through quick-disconnect interfaces, embedded diagnostics, and outage-based calibration procedures that minimize invasive work on the pressure boundary. The planned qualification program, encompassing environmental, seismic, thermal-hydraulic, EMC, and software verification and validation testing, will provide comprehensive evidence that the GWR-based instrument can reliably perform its safety-related functions under all design-basis conditions. The design framework and technical solutions developed in this work are expected to enhance the reliability and maintainability of the i-SMR instrumentation and control system and to serve as a reference for future applications of GWR technology in advanced nuclear reactors.

ACKNOWLEDGEMENTS

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