Development Strategies for Advanced Nuclear Instrumentation Technologies for Innovative Small Modular Reactors

Joonku Lee, Daeil Lee, Bonseung Koo, Sanghoon Bae, Youngwoong Kim
KAERI (Korea Atomic Energy Research Institute)
DAEDEOK-DAERO 989BEON-GIL, YUSEONG-GU, DAEJEON, South Korea
jklee@kaeri.re.kr, daeillee@kaeri.re.kr, bskoo@kaeri.re.kr, shbae@kaeri.re.kr, kywave@kaeri.re.kr

ABSTRACT

Small Modular Reactors (SMRs), unlike existing large-capacity power reactors such as the APR1400 and OPR1000, integrate key components such as the reactor and steam generator, offering advantages in safety, usability, and other aspects. These have garnered global attention, with a total of 71 reactor types currently under development. Miniaturization of innovative SMRs requires miniaturization, integration, and optimization of process variable/condition monitoring measurement sensors. Furthermore, AI-based fault diagnosis capabilities are expected in innovative SMRs, necessitating optimal sensing technologies for equipment condition monitoring. Accordingly, to enhance autonomous operation performance and safety within power plants, a multi-purpose, high-precision measurement system will be developed through the development of technologies such as fiber-optic distributed sensors, low-power wireless sensing, process measurement sensors, and innovative SMR neutron measurement and condition monitoring measurement systems. This will contribute to the safety and economic feasibility of innovative SMRs.

Keywords: *Small Modular Reactor, Advanced nuclear instrumentation, Fiber-optic distributed sensors, RCS flow measurement, GWR-based level measuring, ex-core neutron flux monitoring*

1 INTRODUCTION

Advanced nuclear power systems, including innovative small modular reactors (i-SMRs), require highly reliable sensing technologies capable of operating under harsh environments characterized by high temperature, radiation, pressure, and limited accessibility. Conventional sensing technologies used in nuclear power plants require careful consideration and further improvement for operation in such environments, particularly under more severe temperature and radiation conditions, as well as in systems with complex cabling and limited spatial coverage.

Miniaturization of innovative SMRs requires miniaturization, integration, and optimization of process variable/condition monitoring measurement sensors. Innovative SMRs are expected to introduce AI-based fault diagnosis capabilities, requiring optimized sensing technologies for facility condition monitoring to support these capabilities. Consequently, to enhance autonomous operation performance and safety within power plants, the goal is to develop a multi-purpose, high-precision measurement system. Fiber-optic distributed sensors, low-power wireless sensing, process measurement sensors, and neutron measurement technologies will be optimized and applied to innovative SMRs. This will enhance the safety and economic feasibility of innovative SMRs. Due to the design characteristics of innovative SMRs, the primary components are integrated within the reactor vessel, limiting the installation and deployment space for sensors and instruments for safety diagnosis.

This paper presents the current development status and strategies for fiber-optic distributed sensors, low-power wireless sensing, process measurement sensors, and innovative SMR neutron measurement and monitoring systems scheduled for application, in order to enhance the safety and economic efficiency of innovative SMRs.

2 NECESSITY OF DEVELOPMENT OF ADVANCED MEASUREMENT AND SENSING TECHNOLOGIES AND GLOBAL TRENDS

The innovative Small Modular Reactor (i-SMR) currently under development in South Korea, rated at approximately 170 MW, employs a highly integrated reactor pressure vessel (RPV) configuration that incorporates the reactor core, pressurizer, steam generator, and reactor coolant pump within a single vessel. This compact integral arrangement markedly enhances passive safety characteristics and mitigates severe accident risks when compared with conventional large-scale reactor designs. However, it also imposes significant constraints on instrumentation deployment and in-service maintainability. The lessened volume and structural constraints of both the RPV and containment create substantial challenges for the optimal placement and long-term accessibility of safety-critical sensors. Moreover, the environmental conditions proximal to the RPV are considerably harsher than those of traditional reactors. Elevated neutron fluxes in the vicinity of the core accelerate sensor aging, induce material embrittlement, and degrade performance through direct and secondary radiation effects. Advanced nuclear power systems, including innovative small modular reactors (i-SMRs), require highly reliable sensing technologies capable of operating under harsh environments characterized by high temperature, radiation, pressure, and limited accessibility. Conventional sensing technologies used in nuclear power plants require careful consideration and further improvement for operation in such environments, particularly under more severe temperature and radiation conditions, as well as in systems with complex cabling and limited spatial coverage. In this context, as shown in Figure 1, fiber-optic distributed sensing technologies have emerged as a promising innovative solution for nuclear instrumentation and condition monitoring due to its advantages of compact size, environmental robustness, and the ability to perform continuous distributed measurements along a single sensing line.

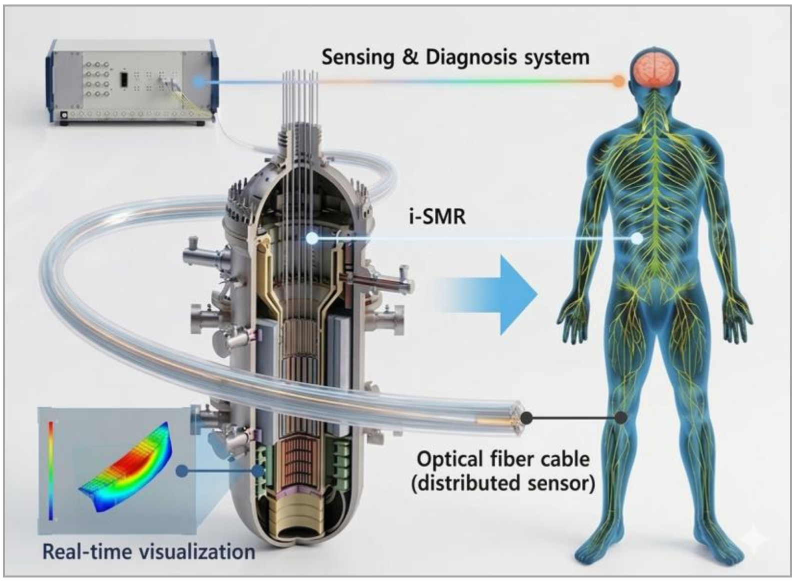


Figure 1: Conceptual Diagram of iSMR Distributed Sensing for Condition Monitoring

Fiber-optic distributed sensors enable simultaneous measurement of temperature, strain, vibration, and radiation over long distances with high spatial resolution, supporting wide-area monitoring of nuclear facilities and critical structures [1,2]. In particular, optical fibers such as F-doped and/or pure-silica-core fibers have demonstrated the ability to maintain sensing performance even under high radiation exposure, highlighting their suitability for nuclear environments [3]. However, technical challenges remain, including radiation-induced attenuation, long-term sensor drift, material degradation in harsh environments, and the need for reliable interrogation and data processing systems. Therefore, systematic research and development are required to establish high-precision, radiation-hardened distributed fiber-optic sensing technologies for nuclear power plants, including sensor material development, harsh-environment packaging, system integration, and rigorous verification and validation through irradiation testing, high-temperature testing, and reactor-relevant demonstrations. Such technologies are expected to play an important role in enabling digitalized and autonomous nuclear power plants by providing real-time, spatially resolved monitoring and supporting predictive maintenance and enhanced operational safety in i-SMRs and next-generation reactors.

"Wireless, low-power, complex sensing technology" is essential for the SMR development competition driven by the Fourth Industrial Revolution and digital transformation, as it can offer cost savings and various benefits across the entire lifecycle of nuclear power plants (design, construction, operation, and decommissioning). In particular, wireless technology is essential for addressing the cost of wired signal cables, which account for the largest portion of nuclear power plant maintenance costs. Companies such as Rolls-Royce SMR in the UK, Westinghouse SMR in the US, and INL Microreactor in the US are accelerating the development of wireless technology. When wireless technology was applied to equipment condition monitoring at commercial nuclear power plants in the United States (e.g., Comanche Peak Nuclear Power Plant), the daily work time of workers was reduced by 4 hours, and in the case of Arkansas One Nuclear Power Plant, wireless sensors were installed on cooling blowers to prevent losses due to unexpected shutdowns

The deployment of ultrasonic flow measurement systems in the reactor coolant system (RCS) of innovative Small Modular Reactors (i-SMRs) poses multifaceted engineering challenges. Unlike conventional large-scale nuclear power plants, the compact and highly integrated nature of i-SMRs severely restricts the available piping layout space. Ultrasonic flowmeters traditionally require a minimum length of straight pipe both upstream and downstream to ensure steady-state flow and to minimize disturbances that could affect measurement accuracy. In light of i-SMR design, securing the recommended straight pipe sections—typically ten times the pipe diameter—is extremely difficult due to the dense and compact arrangement of reactor vessel components, high levels of integration, and the necessity of minimizing plant footprint for modular deployment scenarios [4]. In combination with the elevated temperature and pressure regimes intrinsic to the primary circuit, these factors collectively threaten the durability and measurement accuracy of ultrasonic flow metering devices used for reactor coolant monitoring. The susceptibility of conventional sensor materials to neutron-induced degradation, together with signal attenuation across the thickened RPV walls, underscores the necessity for instrumentation solutions engineered for SMR environments.

The application of Guided Wave Radar (GWR) technology for measuring the pressurizer level in the Innovative Small Modular Reactor (i-SMR) is necessary, 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.

Since the ex-core neutron flux monitoring of innovative SMRs possesses different environments and characteristics compared to that of commercial reactors, it is necessary to establish monitoring requirements specialized for innovative SMRs and design the monitoring system accordingly. Ex-core neutron flux monitoring for innovative SMRs takes place in harsher environments compared to commercial reactors, and in the event of an accident, the system is subjected to high temperatures, high pressures, and flooding. Under these conditions, ex-core neutron flux monitoring for SMRs must be carried out by fully reflecting design characteristics and requirements from the initial design stage.

The “Ex-core Neutron Flux Monitoring System” (ENFMS) is a critical facility for the safe operation of nuclear power plants, monitoring the core power status and providing signals to the reactor control and protection systems. ENFMS provides safety-grade signals to the protection system, which generates plant shutdown signals, and to the monitoring system after an accident. Furthermore, it is a critical facility that provides control class signals to the reactor control system during reactor power operation and monitors core safety during fuel replacement and the attainment of initial criticality. ENFMS provides power signals to the reactor protection/monitoring system within the power operation range using measured neutron flux, and provides source zone signals to the main control room and containment building to monitor the core status during the initial startup of the power plant. It is crucial that ENFMS technology be developed from the early stages of innovative SMR development to ensure connectivity with in-core instrumentation, ex-core instrumentation signal processing systems, and protection systems.

3 DEVELOPMENT STATUS AND STRATEGY FOR ADVANCED SENSING TECHNOLOGIES FOR INNOVATIVE SMR APPLICATIONS

In SMR design, the following factors influence the selection of NSSS sensors: 1) the containment vessel (CNV) fills with water during refuelling, 2) the sensor installation space is between the reactor vessel and the containment vessel, 3) limited accessibility between the RPV and CNV, 4) limited accessibility, and 5) exposure to high temperatures and high radiation conditions.

Therefore, along with these design constraints, advanced measurement technologies must be implemented to ensure autonomous operation and high-precision measurement.

3.1 Multi-parameter Distributed Sensing

3.1.1. Development of radiation-resistant optical fiber

Silica optical fibers are widely used in communication and sensing systems due to their low loss, wide bandwidth, and immunity to electromagnetic interference. However, their deployment in radiation-rich environments, such as nuclear power plants, space missions, and high-energy physics facilities, is limited by radiation-induced attenuation (RIA), which arises from defect formation in the silica network under ionizing radiation [5].

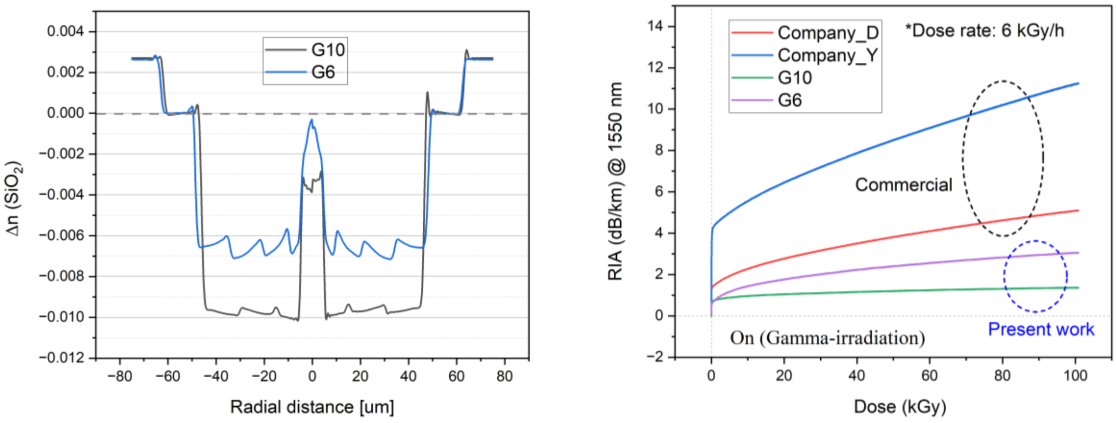


Figure 2: Refractive index profiles of the fabricated optical fibers with different fluorine doping level (left), radiation-induced attenuation of the fibers with respect to exposed dose (right)

Suppressing RIA is therefore essential for reliable long-term operation. Pure-silica-core (PSC) fibers are known to exhibit superior radiation resistance compared with Ge-doped fibers due to the absence of Ge-related defect precursors. In addition, fluorine doping further enhances radiation resistance by reducing oxygen-related defect precursors and modifying defect formation pathways [6].

In this study, optimized compositions of PSC and fluorine-doped optical fibers (G6 and G10) were developed in collaboration with Taihan Fiberoptics Co., Ltd. to enhance radiation resistance, and their radiation response at 1550 nm was investigated under gamma-ray irradiation. In particular, a gamma-ray pre-irradiation technique with a dose of 300 kGy was applied to improve RIA characteristics. The results shown in Figure 2 demonstrate that both the dose-dependent RIA and saturation behavior were significantly improved compared with those of commercially available radiation-resistant fluorine-doped PSC fibers.

3.1.2. Leak detection and localization

Since nuclear power plants (NPPs) utilize high-temperature, high-pressure coolants and radioactive materials, vapor leak detection and localization are essential to prevent severe safety incidents. However, early detection of small leaks and accurate localization within insulated pipes remain challenging due to the presence of surrounding insulation materials. To address this limitation, we propose a high-spatial-resolution distributed temperature sensing (DTS) technique based on optical frequency domain reflectometry (OFDR) for early leak detection in NPPs. Real-time vapor leak detection and localization in an insulated pipe were experimentally demonstrated using an optical fiber-based distributed temperature sensor.

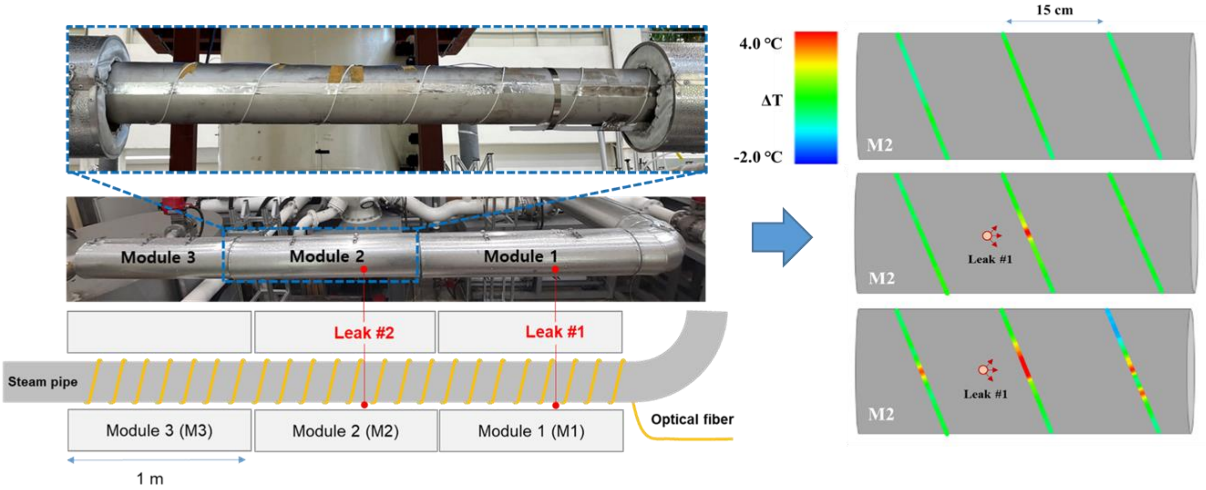


Figure 3: Leak detection in insulated pipe using optical fiber distributed temperature sensor

Leak detection tests were performed on a small-scale NPP testbed at KAERI to simulate high-temperature, high-pressure leakage conditions in an insulated steam pipe. An optical fiber cable was helically wrapped around the pipe (diameter: 11.5 cm) with a pitch of 15 cm. Leaks were generated using separate valves under operating conditions of approximately 3 bar and 120 °C. Since the leakage points were located at the bottom of the insulation modules, initial temperature fluctuation peaks were observed at fiber positions corresponding to the bottom of the pipe following leakage. Figure 3 presents the measured temperature distribution mapped onto the insulated pipe. Temperature variations are visualized using a color scale, providing an intuitive representation of spatial temperature changes induced by the leak. In conclusion, the proposed leak detection approach based on optical fiber distributed temperature sensing enables rapid and accurate identification of both the occurrence and location of small leaks within insulated pipes in the NPP pressure boundary.

3.1.3. Pipeline structural health monitoring

To enhance the safety of operating nuclear power plants, there is a growing need for monitoring technologies capable of continuously observing the condition of structures with limited accessibility while ensuring high accuracy. Distributed fiber-optic sensors require minimal installation space and are well suited for measuring strain or temperature over a wide range. These sensors are extremely thin and flexible, and can be easily attached to structures, even in curved regions, making them ideal for capturing the overall response distribution of a structure.

An OFDR-based distributed strain sensing technique was applied to monitor the strain distribution of a small metallic pipe. An optical fiber was installed linearly along the bottom of the pipe to enable spatially resolved strain measurements. For validation, four commercial strain gauges (FLAB series, TML) were co-located and used for comparison under applied loading conditions. As shown in Figure 4, the distributed fiber-optic sensor successfully captured continuous strain profiles along the pipe, demonstrating higher spatial resolution and broader coverage than conventional point-based strain gauges. These results highlight the potential of distributed fiber-optic sensing for precise and wide-area structural health monitoring (SHM) of nuclear piping systems.systems.

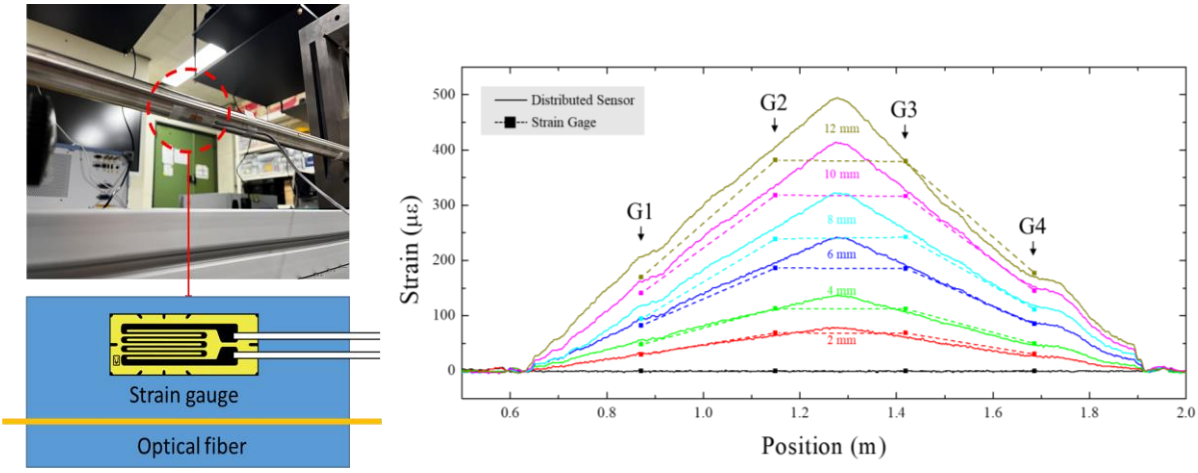


Figure 4: Strain distribution along the pipe measured by distributed sensing (line), compared with strain gauge (G1–G4) measurements

3.1.4. Distributed radiation dosimetry

In NPP condition monitoring systems, sensors and instrumentation are often exposed to high-radiation environments, which can lead to material degradation and signal drift. Distributed sensing techniques using radiation-sensitive specialty optical fibers enable real-time measurement of radiation dose distribution in sensor-installed regions, allowing for signal compensation and monitoring of abnormal radiation exposure conditions. In this study, the radiation dose distribution from a ^{60}Co gamma source (KAERI-ARTI) was measured using radiation-sensitive P-doped fiber in combination with an optical backscatter reflectometry (OBR-4613) system. To introduce spatial variation in radiation exposure, two lead (Pb) shielding blocks (0.2 m each) were partially applied along the fiber, creating distinct dose regions. The measured results were compared with those obtained from conventional alanine dosimeters (D1-D5), as shown in Figure 5. The results demonstrate that the distributed radiation sensing technique enables real-time and remote monitoring of accumulated radiation dose distribution over the entire sensing region using a single fiber line, highlighting its effectiveness under specific conditions compared with conventional point-based dosimetry.

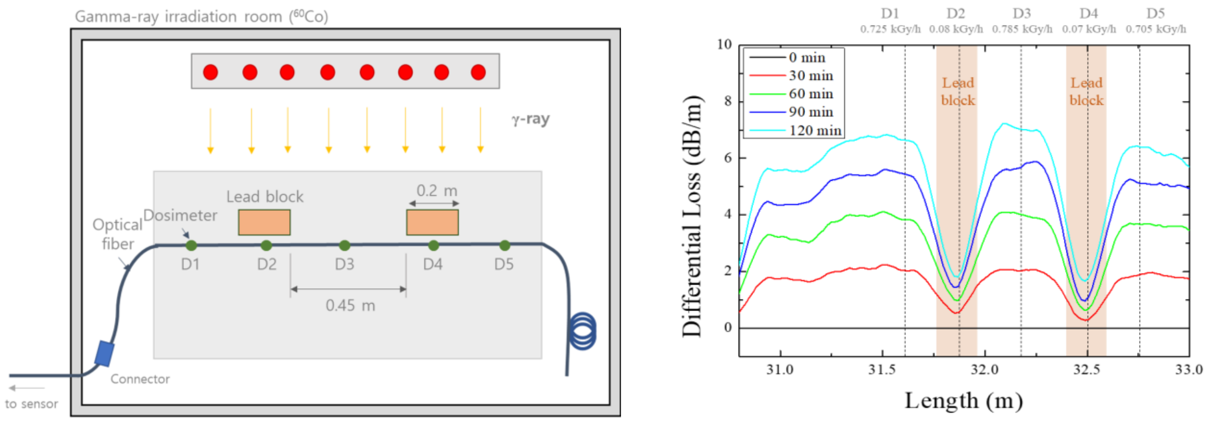


Figure 5: Experimental results of radiation dose distribution monitoring with comparison to alanine dosimeters (D1–D5)

3.2 RCS Flow Measuring

3.2.1 RCS flow Measurement of Ultrasonic flow meter

The ultrasonic flow measurement system offers a sophisticated, non-intrusive technique for quantifying fluid flow within power plants, including the RCS. Fundamentally, this method utilizes the propagation characteristics of high-frequency ultrasonic waves transmitted through the fluid medium. By precisely measuring the transit-time of ultrasonic signals between paired transducers located outside the process pipe, the system accurately determines the fluid's velocity profile. Furthermore, advanced ultrasonic flowmeters leverage digital signal processing algorithms and can be integrated with supplementary sensor data such as real-time fluid density, temperature enabling correction on thermophysical variations and enhanced measurement accuracy. This approach minimizes flow disturbance, eliminates the risk of leakage paths, and enables reliable, continuous monitoring of RCS flow under the i-SMR environments.

3.2.2 Functional element of ultrasonic flowmeter for RCS flow measurement

The components and functions of the ultrasonic flow meter are illustrated in Figure 6. First, the ultrasonic transducer uses at least one pair of sensors to transmit and receive ultrasonic signals through the fluid. The measuring method here is the Time-of-Flight (ToF) technique which measures the velocity by calculating the distance and signal time difference between the two sensors. The wedge has function to adjust the angle at which the ultrasonic signal traverses the fluid, directing the propagation of the waves and finding the optimal angle for more accurate measurements. The material of the wedge varies depending on the fluid's characteristics, and for case of the i-SMR, a ceramic material is chosen due to its high-temperature properties.

The MI cable is used to reliably transmit the high-frequency signals generated by ultrasonic transducers and to ensure stable communication between the sensor and the control unit. The cable is designed to withstand electromagnetic interference, high temperatures, and radiation environments in particular. The control unit has function of the stable operation of the system, comprising a power supply unit, a DC converter for precise voltage regulation, a controller for time synchronization and control of the transceiver unit, and a signal processing unit that processes the received signals and converts them into data for measuring fluid velocity. Additionally, the system includes an analog-to-digital converter and an amplifier [5].

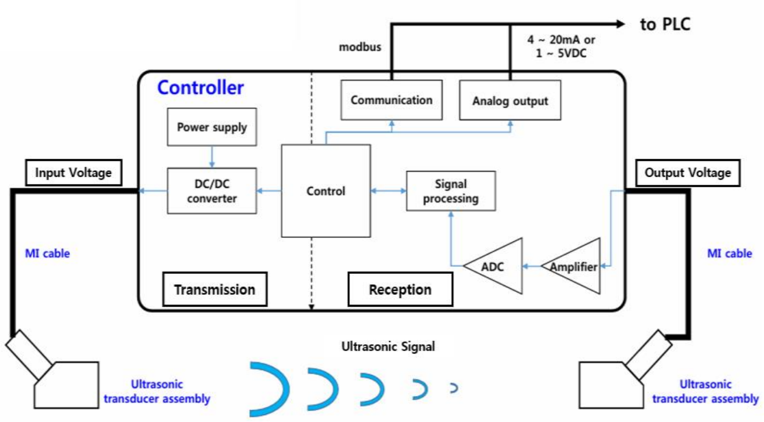


Figure 6: Structure of ultrasonic signal flow

3.2.3 Various approach for addressing technical issures

Conventional ultrasonic transducers employed in industrial flow measurement applications are generally engineered to produce excitation pulses exceeding 300 VDC at operational frequency typically below 400 kHz, and are rated for sustained usage within ambient temperature up to approximately 80 °C. These designs have been optimized for moderate conditions, where their piezoelectric materials, electrical insulation, coupling layers, and housing are not subjected to severe thermal or radiological stress. In contrast, installation in the i-SMR presents a fundamentally different set of technical challenges. The external surface temperature of the reactor pressure vessel (RPV), which serves as the mounting location for ultrasonic sensors, consistently exceeds 320 °C under normal operating conditions, surpassing conventional transducer thermal ratings. This environment is further compounded by elevated gamma and neutron radiation fields and mechanical stresses induced by high pressures commonly encountered in nuclear service.

These extreme conditions necessitate the development and qualification of ultrasonic transducers from radiation-resistant piezoelectric materials; high-temperature, radiation-hardened cabling; and robust coupling/encapsulation systems capable of maintaining acoustic integrity and electrical performance under prolonged exposure to 300 °C and pressures exceeding 10 MPa. Furthermore, the transducers must retain their functionality and durability during cumulative radiation-induced degradation and thermal cycling, ensuring signal generation and acquisition for long-term operation within harsh i-SMR environment condition. Accordingly, this chapter systematically proposes a range of advanced engineering and material technologies being devised to address these technical issues with focused on enhancing sensor survivability, accuracy, and maintainability in high-temperature, pressure, radiation environments.

3.3 GWR-based Pressurizer Level Measuring

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.

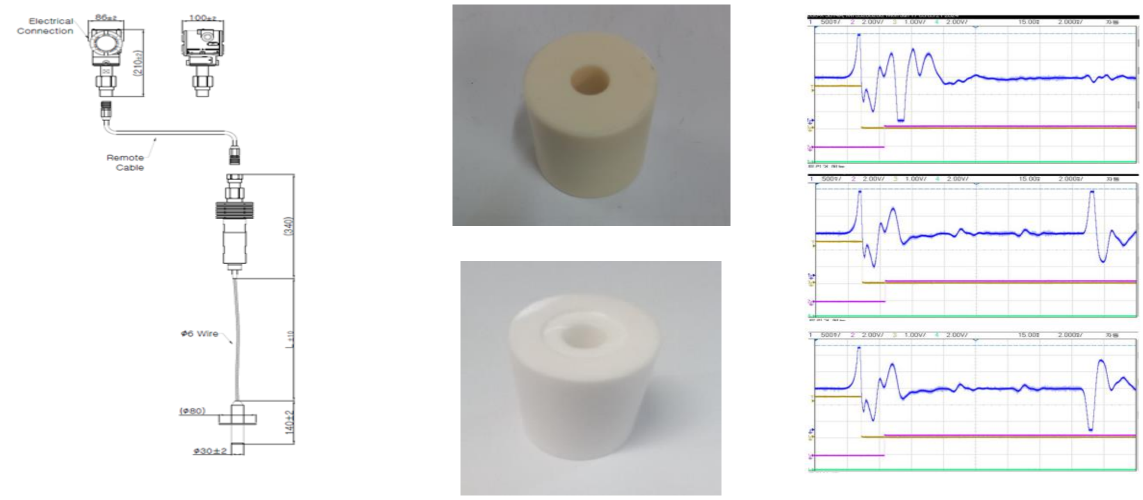
This study presents guided wave radar (GWR) technology, based on time-domain reflectometry (TDR), as a minimally invasive, top-mounted solution for i-SMR pressurizer level measurement, as shown in figure 7.

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 study addresses key design elements for signal integrity, penetration and safety-class requirements, installation constraints, and the planned qualification program.

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 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.



a. GWR probe module configuration

b. Probe module ceramic material

c. Probe Module TDR Transmit/Receive Waveforms

Figure 7: GWR Level Instrumentation

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.

3.4 Ex-core Neutron Flux Monitoring

Ex-core neutron flux monitoring measures reactor power by detecting neutrons leaking from the reactor vessel. The typical measurement range is about 10 decades, covering from 2E-8 - 200% of full power. Neutron flux evaluation verifies whether sufficient neutron flux is available at the expected detector positions. This evaluation provides basic design data to find the best location in terms of neutron leakage. This will provide information in determining the best installation position, installation process. In addition, it will help and guide for the detector development of i-SMR in the future.

The neutron flux distribution and characteristics of energy spectrum at the expected position of Ex-core detector installation is evaluated for the detailed design of the Ex-core Neutron Flux Monitoring System for i-SMR. Two independent code systems are used in a complementary manner to ensure analytical reliability and physical validity.

DORT, a transport analysis code developed by the Oak Ridge National Laboratory solves the transport equation based on the 2D Discrete Ordinates (Sn) method. Additionally, the multi-group cross-section table generated via the GIP code using the DLC-185/BUGLE-96 library is applied[7,8,9]. MCNP, a monte carlo code developed by Los Alamos National Laboratory is general purpose code that can be used for neutron, photon, electron transport, including the capability to calculate eigenvalues for critical system[10].

A basic core and reactor vessel model is shown in Figure 8, and overall neutron flux distribution is presented as a contour plot in Figure 9. Both codes shows similar attenuation behaviour. As further away from the center of the core, the neutron flux in all energy intervals shows a trend of exponential decay. Furthermore, a distinct spectrum softening phenomenon is observed, where fast neutrons are moderated and shift toward lower energy regions as they pass through the water and steel shielding. The figure clearly shows the physical behavior of rapid neutron flux attenuation as the neutrons pass through major shielding structures, including the reflector, reactor vessel, and containment vessel. In particular, it was confirmed that the shape of the flux contours was appropriately formed in accordance with the geometric configuration of the internal structures.

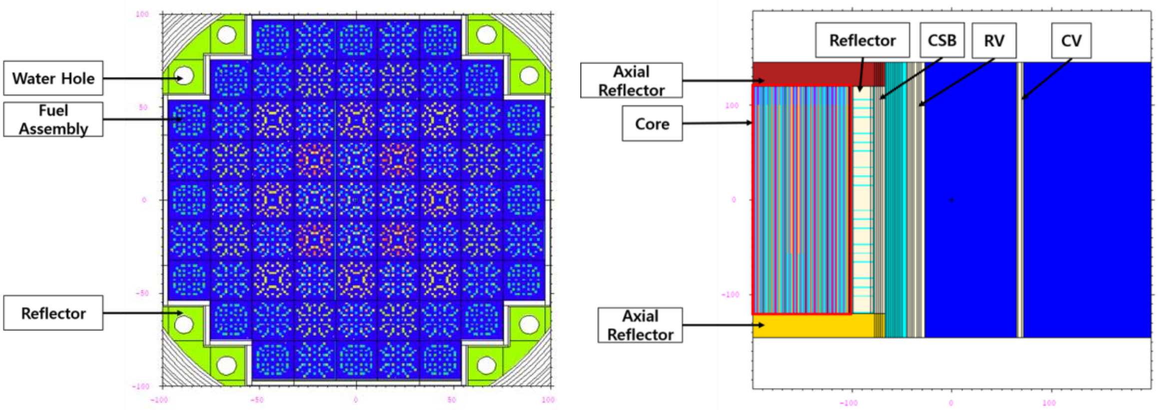


Figure 8: Core and reactor vessel assembly model (MCNP plot)

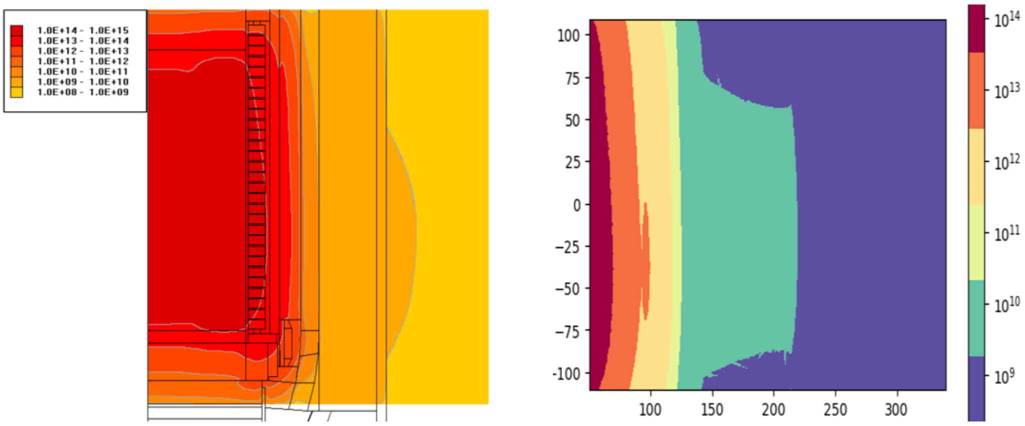


Figure 9: Neutron flux map (DORT & MCNP)

Neutron flux by energy boundary at the outer wall of the containment vessel are summarized in Table 1. Total neutron flux was evaluated at approximately 7.52E+08 n/cm^2-sec based on the MCNP detailed model. The DORT calculation result was evaluated at 1.55E+09 n/cm^2-sec. These values, especially thermal range, is slightly lower than that of convention PWRs, and optimal design of resin material surrounding detector assembly is probable way to increase thermal flux level. In analysis of deep penetration problem, statistical reliability could be guaranteed by implementing variance reduction techniques such as geometry splitting or weight window.

Table 1: Neutron flux at Expected Ex-core Detector Position

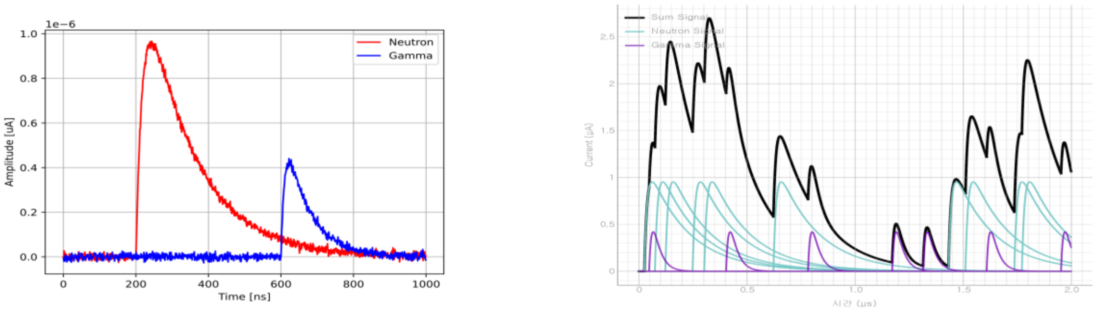
Energy Boundary	**Neutron Flux [n/cm^2-sec]**	
	DORT	**MCNP**
0.0 eV - 0.625 eV	8.21E+05	2.41E+05
0.625 eV – 1 MeV	1.48E+09	7.02E+08
1 MeV – 20 MeV	6.78E+07	4.98E+07
Total	1.55E+09	7.52E+08

This evaluation ensured the reliability of the results in analysing the Ex-core neutron environment using dual code systems. This work provides a solid technical foundation for the detailed design of i-SMR Ex-core neutron flux monitoring system. Furthermore, the evaluation method and process established through this study can be directly utilized for future design tasks related to Ex-core instrumentation development.

To verify the performance of the ex-core neutron monitoring drawer, testing in a reactor-like environment is essential. However, actual testing in operating power plants or research reactors is limited by safety regulations, significant costs, and operational constraints. Therefore, simulation-based modeling and testing of the drawer are required to overcome these time and economic limitations.

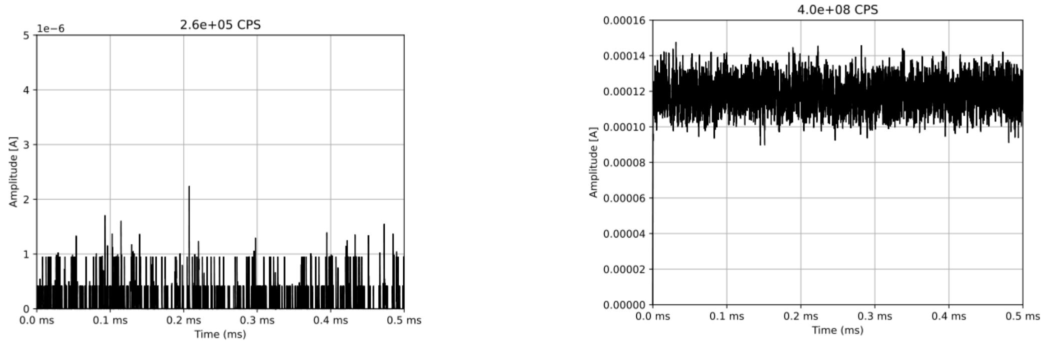
The simulation is divided into a signal generator and a signal processor. The signal generator simulates the physical characteristics of the actual neutron detector's output and provides this input to the signal processor. As shown in Figure 10-a, the detector measures individual pulses of neutrons (red line) and gamma rays (blue line). Because these pulses occur randomly, they overlap on the time axis, causing a pulse pile-up effect as shown in Figure 10-b. The final detector output consists of these overlapping signals.

This pile-up effect leads to an overestimation when measuring the neutron signal. In the low-power range, as shown in Figure 10-c, this pile-up is minimal, so measuring the count rate is not a major issue. However, as the reactor power increases, the signal changes into an AC noise form, as seen in Figure 10-d. Therefore, the signal processor requires specific processing techniques that account for these signal characteristics.



a. Single Pulse Shape

b. Pulse pile-up phenomeno

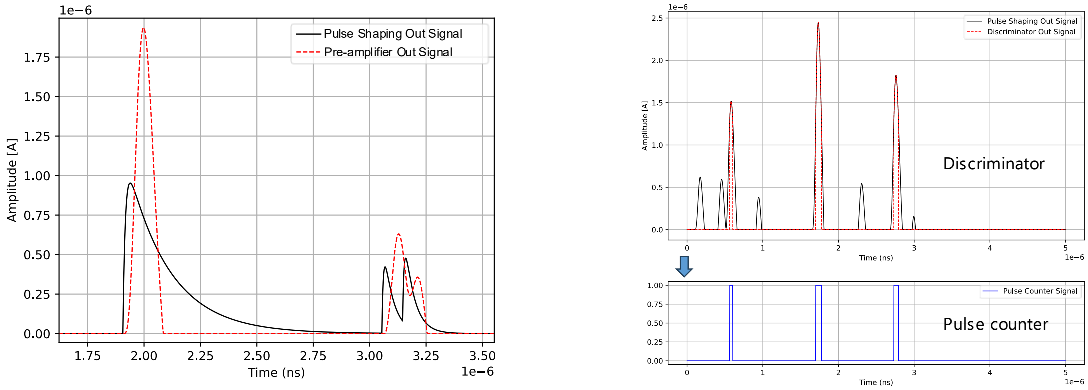


c. Low power range (individual pulses)

d. High power range (AC noise)

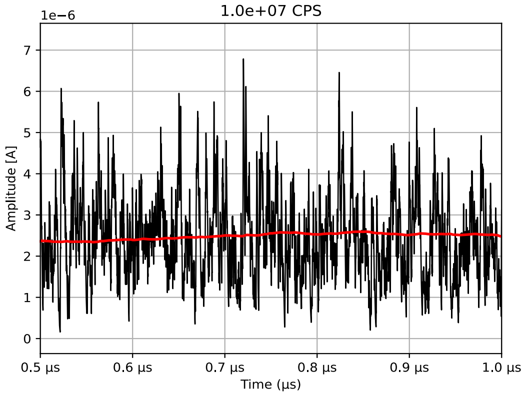
Figure 10: Result of signal generator

The signal processor converts the circuits and functions of the analog drawer into a digital model. Based on the simulated input signal, it uses an algorithm to calculate the logarithmic and linear outputs, which are the core measurements of the ex-core neutron drawer. To measure the count rate in the pulse range (low power), the processor shapes the input pulses before measuring them, as shown in Figures 11-a and 11-b. When the power increases and the signal turns into AC noise, it calculates the Mean Square Voltage (MSV) signal using the Campbelling method, as seen in Figure 11-c.



a. Pulse shaping

b. Pulse counting



c. MSV processing

Figure 11: Result of signal processor

4 CONCLUSION

Securing core technologies through the development of advanced measuring instruments is essential for securing Korea's unique brand of innovative SMRs. Developing environmentally distributed sensor technology suitable for the innovative SMR environment and structure will complement the limitations of existing point-type sensor technology for nuclear power plants and enable more precise and reliable SMR condition monitoring.

This study demonstrated the development and application of distributed fiber-optic sensing technologies for condition monitoring in nuclear power systems, including i-SMRs. Radiation-resistant PSC and fluorine-doped fibers were developed and exhibited improved RIA performance.

Multiple sensing applications, including leak detection using distributed temperature sensing, structural health monitoring via distributed strain sensing, and radiation dose distribution measurement, were experimentally validated. These results confirm the effectiveness of distributed fiber-optic sensing for real-time, wide-area, and high-resolution monitoring in nuclear power plants.

This study has presented the design concept for a RCS flow measurement and GWR pressurizer level measurement system tailored to the i-SMR integral reactor configuration. As a water flow/level measuring device capable of withstanding extreme environments, it can be utilized in small modular reactors such as APR+ and SMART nuclear power plants, offshore SMRs, and innovative SMRs.

Furthermore, by incorporating innovative ex-core neutron flux monitoring technology and monitoring devices into innovative SMRs, we can secure optimal, proprietary ex-core neutron flux monitoring technology and devices, meeting the requirements. The development of proprietary ex-core neutron flux monitoring technology and devices will enable us to quickly respond to industry demands and changes in the licensing environment, and enable detailed analyses using the latest methodologies and evaluation data. The developed ex-core neutron flux monitoring technology can be applied to the design of various cores, including commercial nuclear power plants, research reactors, and next-generation reactors. In addition, integration with other sensors, instrumentation, and diagnostic technologies under reactor-relevant conditions will be essential to enable practical deployment in Generation IV reactors and i-SMRs.

ACKNOWLEDGEMENTS

This work was supported by the National Research Foundation of Korea (NRF) funded by the Korea government (MSIT: Ministry of Science and ICT) (No. RS-2023-00258052).

REFERENCES

[1] J. Wu et al., "Distributed fiber sensors with high spatial resolution in extreme radiation environments in nuclear reactor cores," Journal of Lightwave Technology, vol. 39, no. 14, pp. 4873–4883, 2021.

[2] A. Rovera, A. Tancau, N. Boetti, M. D. Dalla Vedova, P. Maggiore, and D. Janner, "Fiber optic sensors for harsh and high radiation environments in aerospace applications," Sensors, vol. 23, no. 5, p. 2512, 2023.

[3] S. Girard et al., "Overview of Radiation Effects on Silica-Based Optical Fibers and Fiber Sensors," IEEE Transactions on nuclear science, vol. 72, no. 4, pp. 982–1020, 2025.

[4] “Instrumentation and Control Systems for Advanced Small Modular Reactors”, IAEA Nuclear Energy Series, 2017.

[5] S. Girard *et al.*, "Overview of radiation induced point defects in silica-based optical fibers," *Reviews in Physics,* vol. 4, p. 100032, 2019.

[6] T. Shikama, T. Kakuta, N. Shamoto, M. Narui, and T. Sagawa, "Behavior of developed radiation-resistant silica-core optical fibers under fission reactor irradiation," Fusion Engineering and Design, vol. 51, pp. 179–183, 2000.

[7] “RSICC Computer Code Collection-DOORS3.2,” CCC-650, ORNL, Apr., 1998.

[8] “RSIC Data Library Collection Bugle-96.” DLC-185, ORNL, Mar., 1996.

[9] W. A. RHOADES, “The GIP Program for Preparation of Group –Organized Cross-Section Libraries,” ORNL, Apr., 1978.

[10] “MCNP-A General Monte Carlo N-Particle Transport Code,” CCC-810, LANL, Aug., 2013.