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Development of *In situ* Underwater Radiation Monitoring Systems

Wanook Ji, Myoung Jung Kim, Kun Ho Chung, and Young-Yong Ji*

Environmental Safety Technology Research Division, Korea Atomic Energy Research Institute
111, 989beon-gil, Daeduk-daero, Yuseong-gu, Daejeon, Republic of Korea

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The real-time monitoring of marine radioactivity is essential for rapid response to radiological events, particularly in Korean coastal waters influenced by radionuclide transport from the Fukushima region. Conventional sampling-based analyses provide high accuracy but lack temporal continuity and broad spatial coverage. To overcome these limitations, in this study, we developed and evaluated a series of *in situ* underwater gamma-ray detection systems [Monitoring of Ambient Radiation of KAERI-Underwater (MARK-U) series], each optimized for seabed monitoring, dissolved radionuclide measurement, on-site sample analysis, and maritime mobile surveys. The systems employ NaI(Tl) and $CeBr_3$ scintillation sensors integrated with pressure-resistant housings, embedded electronics, and real-time data communication technologies for underwater radiation sensing. Detection efficiencies of the sensors were calculated using Monte Carlo N-Particle (MCNP) simulations and verified through field experiments. The results demonstrate that the MARK-U systems provide stable, *in situ* gamma-ray spectrometry with significantly improved temporal resolution and operational efficiency over conventional methods. These integrated underwater systems support enhanced marine radiological surveillance and rapid-response capability for future environmental monitoring and emergency situations.

1. Introduction

The monitoring of radioactivity in the marine environment is essential for ensuring environmental safety, protecting public health, and maintaining sustainable marine ecosystems. Korea, located adjacent to the Fukushima Daiichi Nuclear Power Plant (FDNPP), is geographically and oceanographically positioned to be directly affected by the dispersion of radioactive materials released from nuclear accidents. Korean coastal waters—including the East Sea (Sea of Japan), Yellow Sea, and southern waters are connected to ocean currents that can transport radioactive nuclides discharged from the Fukushima region. Indeed, elevated concentrations of anthropogenic radionuclides such as ^{134}Cs and ^{137}Cs were observed in Korean waters from 2011 to 2012.[1] This proximity underscores the importance of Korea as a critical

*Corresponding author: e-mail: yyji@kaeri.re.kr
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observation area for the international monitoring of marine radioactivity dispersion. Marine radioactivity monitoring generally employs two complementary approaches: sampling-based monitoring and *in situ* underwater radiation monitoring. In sampling-based monitoring, seawater, sediment, or biota samples are collected in the field and subsequently analyzed in laboratories using high-purity germanium (HPGe) gamma spectrometry, beta counting, or mass spectrometric techniques. Samples are usually collected at specific depths with Niskin bottles, filtered to separate particulate and dissolved fractions, and pretreated through adsorption or evaporation to concentrate radionuclides. This approach provides highly accurate and precise results with extremely low detection limits and allows for standardized international comparisons.[2,3] However, the process requires several days to weeks for data analysis, making real-time monitoring impossible. Furthermore, the limited number of sampling sites restricts spatial resolution, making it difficult to identify localized anomalies promptly.

In contrast, *in situ* underwater radiation monitoring directly measures radiation within the water column using submerged detectors.[4–7] These systems typically comprise gamma-ray sensors—such as NaI(Tl), CsI(Tl), or $LaBr_3$(Ce)—encased in a waterproof, pressure-resistant housing, along with signal processing electronics, data logging, and communication modules. Although the detection sensitivity of *in situ* systems is lower than that of laboratory-based analyses owing to the strong attenuation of gamma rays in water (e.g., ^{137}Cs can be reliably detected at concentrations of several $Bq{\cdot}L^{-1}$ or higher), they provide substantial advantages. *In situ* systems offer real-time and continuous measurements, improved spatial and temporal coverage through mobile operation, and efficient, remote, or autonomous functionality. Owing to these benefits, many countries have been developing and deploying underwater radiation monitoring systems to enhance the responsiveness and coverage of their marine surveillance networks.[7,8]

The complementary use of both approaches is therefore crucial to improving the reliability and efficiency of future marine radioactivity monitoring systems. Particularly after the Fukushima accident and the subsequent discharge of Advanced Liquid Processing System (ALPS)-treated water, public and scientific interest in the real-time detection of radionuclide dispersion has intensified. To address this demand, in this study, we present the design and development of *in situ* underwater gamma-ray spectrometers capable of long-term stable operation and real-time spectral acquisition in marine environments. The developed system integrates NaI(Tl) and $CeBr_3$ scintillation sensors with signal processing electronics, a waterproof pressure housing, and a communication module into a compact, durable configuration. The design aims to ensure mechanical and environmental resilience against hydrostatic pressure and temperature while achieving a high detection efficiency and a low minimum detectable activity (MDA). Monte Carlo simulations and field measurements were conducted to characterize detector responses and assess the effects of geometry and environmental parameters. Experimental results were quantitatively validated against laboratory measurements, and calibration functions were derived.

The findings of this research are expected to provide a technical foundation for the enhancement of Korea's marine radioactivity monitoring network and for establishing a rapid-response capability during potential radiological emergencies.

2. Development of Underwater Radiation Detection System

The core strategy for the development of *in situ* underwater radiation measurement is to maximize the detection efficiency by capturing gamma rays incident from the detector. Owing to the high attenuation effect of aquatic media, most underwater detectors operate while fully submerged in seawater, thereby establishing an approximately 4π detection geometry.[9–12] In the detector system, scintillation sensors are primarily utilized owing to their high detection efficiency.[12] NaI(Tl) is the most widely used scintillator for marine radioactive monitoring, offering advantages such as high light yield, excellent detection efficiency, and low cost. $CeBr_3$ and $LaBr_3$(Ce) scintillators,[13] which offer improved energy resolution, are utilized for underwater detectors to achieve a lower MDA, and also the cadmium zinc telluride (CZT) semiconductor with a large-volume monolithic crystal is utilized for long-term seabed monitoring owing to its low power consumption.[6,7,14] The detectors are protected from high water pressure and seawater corrosion with a specialized housing. The housing materials are selected on the basis of the balance between radiation transmissivity and mechanical strength.

3. *In situ* Underwater Bottom Monitoring System

3.1 Detector configuration

The Monitoring of Ambient Radiation of KAERI-Underwater 1 (MARK-U1) system was developed to evaluate the deposition of radioactive materials dispersed into the underwater environment. The detector was designed to operate at water depths of up to 100 m and housed in a 10-mm-thick stainless-steel (STS316) cylindrical enclosure to ensure structural integrity and water resistance (see Fig. 1). A 3″φ × 3″ NaI(Tl) scintillator was installed inside the housing. Because the primary objective of this system was to quantify radionuclides deposited on the seabed, directional shielding was implemented so that gamma radiation was measured exclusively from the downward direction. For this purpose, a 10-mm-thick lead collimator surrounded the detector, leaving only the bottom-facing entrance window exposed toward the sediment surface. The entrance window was constructed from low-density monomer cast nylon (MC-nylon) to minimize gamma attenuation. The detection unit consisted of the NaI(Tl) crystal coupled to a photomultiplier tube (76B76, SCIONIX, Netherlands). The signal output was processed using a multichannel analyzer (HAMPack-527, SIDetection, Korea), which was also integrated within the stainless-steel housing. Data were transmitted via an underwater cable to a surface data controller equipped with a GPS receiver, a Bluetooth transmitter for real-time data transfer, internal storage memory, and a rechargeable battery system supplying power to the detector, MCA, GPS, and communication modules. To evaluate the counting efficiency of the MARK-U1 system, Monte Carlo simulations were performed using 'the Monte Carlo N-Particle (MCNP) code,[15] as shown in Fig. 2. Considering sediment mixing near the surface caused by tidal currents, a cylindrical source geometry was assumed to represent the distributed radionuclide layer. The simulation results indicated that the effective source volume contributing to detector response corresponds to a cylindrical region with a diameter of 30 cm and a depth of 20 cm.

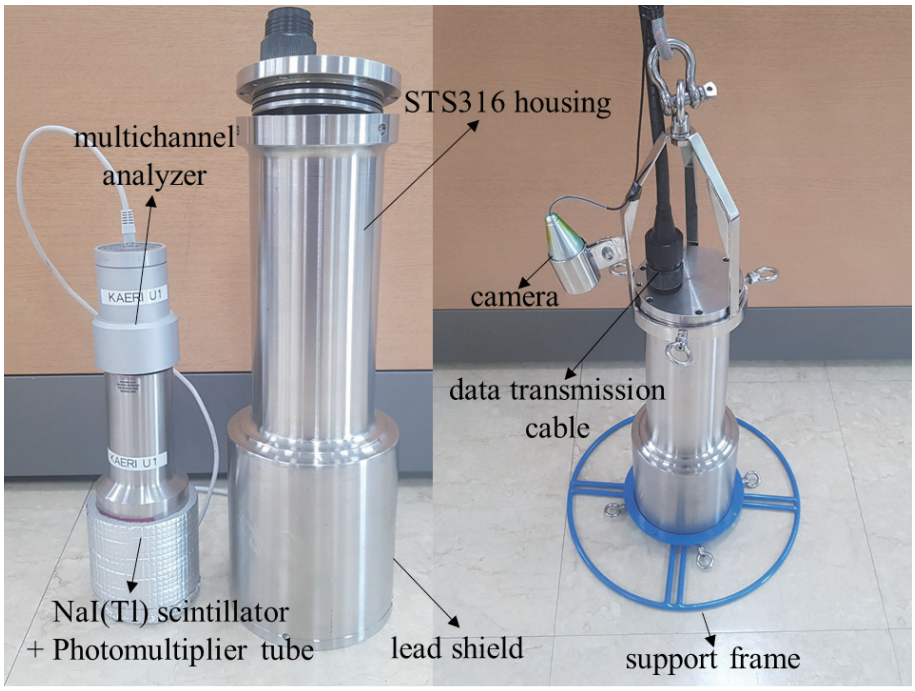

Fig. 1. (Color online) Configuration of the MARK-U1 system.

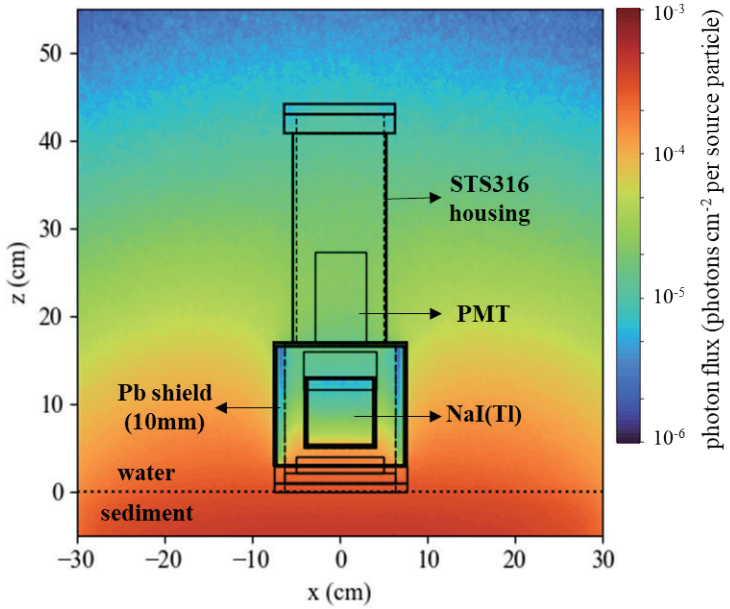

Fig. 2. (Color online) Spatial distribution of photon flux around the MARK-U1 system for a uniformly distributed sediment source.

3.2 Field performance test of MARK-U1 system

To validate the performance of the MARK-U1 system, *in situ* measurements were conducted at a reservoir site. The detector was positioned directly on the riverbed, and each measurement was performed for 120 s. Following the measurement, sediment cores (diameter: 4.9 cm; length: 30 cm) were collected from the same locations and analyzed in the laboratory using an HPGe gamma spectrometry system to determine the reference ^{137}Cs activity concentrations. To evaluate the applicability of the Monte Carlo-derived counting efficiency, the theoretical efficiency obtained from MCNP simulations was applied to the measured net peak count rate at 662 keV to estimate the *in situ* ^{137}Cs activity concentration. As shown in Fig. 3, the activity concentrations estimated using the theoretical efficiency exhibited a strong linear correlation with the laboratory-measured values (R^2 = 0.99). This result confirms that the net peak count rate measured by the MARK-U1 system is directly proportional to the actual ^{137}Cs concentration in the sediment.

However, the slope of the regression line deviated from unity. Linear regression analysis yielded an empirical relationship corresponding to a conversion factor of 79.7 Bq·kg^{-1} per cps for the field measurements, whereas the theoretical model predicted a lower proportionality constant. The consistent linear trend indicates that the discrepancy arises from systematic effects rather than statistical fluctuations. Despite this proportional difference, the high correlation coefficient demonstrates that the Monte Carlo-based efficiency model provides a reliable quantitative framework for the *in situ* monitoring of seabed ^{137}Cs contamination. The results confirm that the MARK-U1 system can effectively estimate radionuclide concentrations under field conditions when appropriate calibration is applied.

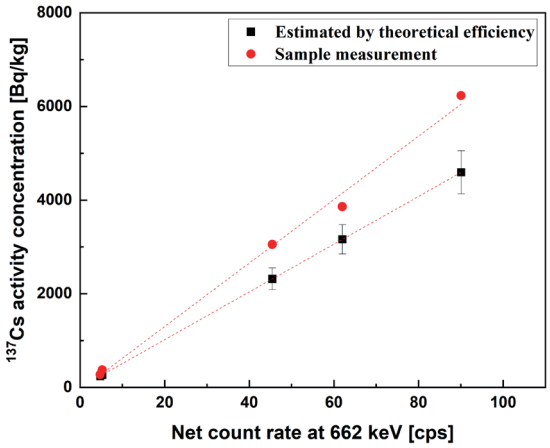

Fig. 3. (Color online) Comparison of ^{137}Cs activity concentrations estimated from theoretical efficiency and sample activity concentration.

4. *In situ* Underwater Monitoring System

4.1 Detector configuration of MARK-U2 system

The MARK-U2 system was developed to measure the activity concentration of radionuclides dissolved in seawater or adsorbed onto suspended particles. Because gamma radiation is significantly attenuated in water, the detector housing was fabricated from low-density MC-nylon rather than stainless steel in order to minimize attenuation effects. Figure 4 presents the configuration and photograph of the completed MARK-U2 system. The housing contains a 3″φ × 3″ NaI(Tl) scintillation detector (76B76, SCIONIX, Netherlands) coupled with a signal processing unit (HAMPack-527, SIDetection, Korea). The acquired spectral data are transmitted to the same surface controller used in the MARK-U1 system via an underwater data cable.

Monte Carlo simulations using the MCNP code were performed to evaluate the detection efficiency in seawater. A spherical source geometry was modeled around the detector to represent a homogeneously distributed radionuclide field in water. The detection efficiency was calculated by incrementally increasing the radius of the spherical source. The simulation assumed a uniform distribution of ^{40}K in seawater. The calculated counting rate increased with source radius and reached approximately 95% of saturation at a radius of 50 cm, and further increases in source radius produced negligible changes in counting rate. Therefore, the effective source volume contributing to the detector response was defined as a sphere of 50 cm radius.

4.2 Field performance test of MARK-U2 system

The performance of the MARK-U2 system was evaluated in a coastal seawater environment. A handheld digital water quality meter (ProDSS, YSI, United States) was used to measure

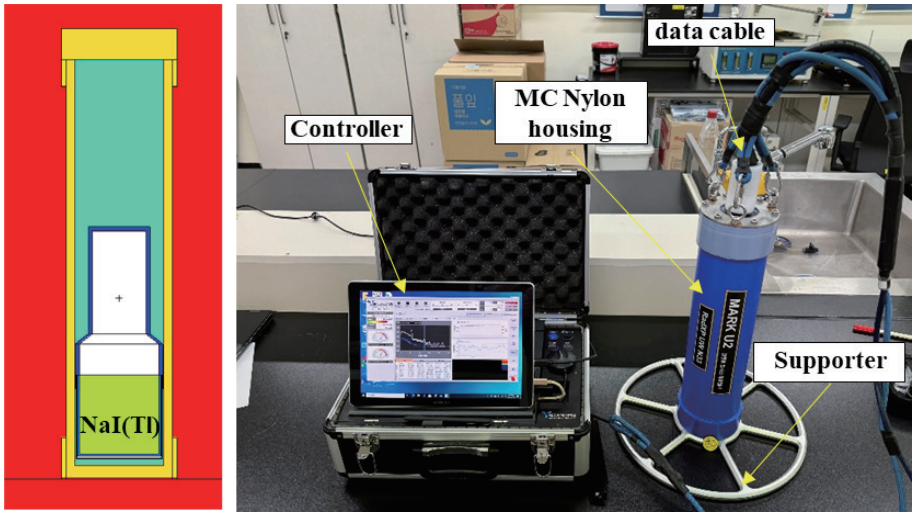

Fig. 4. (Color online) Configuration of the MARK-U2 system.

salinity simultaneously. Figure 5 shows the measured gamma-ray energy spectrum obtained in seawater. The detector was submerged to a depth of approximately 5 m, and each measurement was conducted for 300 s. The activity concentration of ^{40}K was estimated from the net count rate of the 1461 keV gamma peak by applying the theoretical detection efficiency derived from MCNP simulation. The estimated ^{40}K activity concentrations were compared with reference values calculated from measured salinity, assuming natural potassium abundance and isotopic composition. As summarized in Table 1, the difference between the gamma-ray-based estimation and salinity-derived values ranged from 13.7 to 16.9%.

The observed deviation is attributed primarily to the relatively low activity concentration of ^{40}K in natural seawater, which leads to increased statistical uncertainty in net peak counting. Nevertheless, the results demonstrate that the MARK-U2 system can quantitatively estimate dissolved radionuclide concentrations in seawater with reasonable accuracy under field conditions.

5. Buoy-type *In situ* Water Sample Analyzation System

5.1 Detector configuration of MARK-U3 system

The MARK-U3 system is a buoy-type, floating radiation monitoring system designed for the real-time gamma-ray spectroscopic analysis of seawater samples. Its housing has an outer diameter of 420 mm and a height of 454 mm, and contains a 2 L Marinelli beaker for water

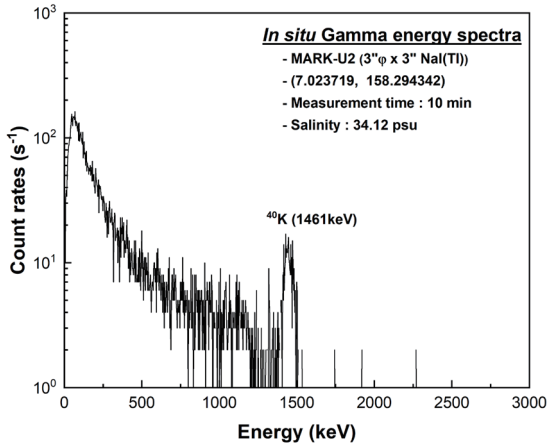

Fig. 5. *In situ* gamma-ray energy spectrum obtained with the MARK-U2 system in surface seawater.

Table 1
Comparison between salinity-derived and gamma-ray-estimated ^{40}K activity concentrations in seawater.

No	$^{40}K_{sal}$ from salinity (Bq/kg)	$^{40}K_{est}$ from γ-ray energy spectrum (Bq/kg)	Error (%) $(^{40}K_{est} - {}^{40}K_{sal})/{}^{40}K_{sal} \times 100$
1	11.94	13.91	16.5
2	11.97	13.99	16.9
3	11.90	13.53	13.7

sampling (see Fig. 6). A 2″φ × 2″ $CeBr_3$ scintillation sensor coupled with a photomultiplier tube (51B51, SCIONIX, Netherlands) was employed to improve spectral discrimination compared with conventional NaI(Tl) detectors. $CeBr_3$ has been reported to exhibit an energy resolution of 3.73% at 662 keV, which is substantially better than 6.65% reported for NaI(Tl).[16] The improved energy resolution is expected to contribute to lower detection uncertainty and improved MDA, particularly for radionuclides with overlapping peaks or low net peak areas. The detector is connected to a signal processing unit (HAMPack-527, SIDetection, Korea) for spectral acquisition. Unlike conventional *in situ* monitoring systems, which measure gamma radiation from the surrounding environment, the MARK-U3 system measures gamma radiation emitted from the water sample contained inside the detector assembly. Seawater is automatically pumped into the sample container using a controlled pumping system, and after measurement, the sample is discharged. To reduce external background radiation, the sample chamber is shielded with a composite structure consisting of 1 mm lead, 0.3 mm copper, and 1 mm stainless steel. A Bluetooth communication module enables remote data transmission and system control, while a rechargeable portable battery supplies power to the detector, electronics, and communication modules.

Monte Carlo simulations were performed to determine the absolute counting efficiency of the MARK-U3 system for the internal water-sample geometry. The sample container was assumed to be completely filled with seawater containing homogeneously distributed natural ^{40}K. The 1461 keV photopeak from the radioactive potassium was simulated, and the full-energy peak efficiency was calculated on the basis of the net peak count rate in the 1461 keV region. The simulation results provided the conversion factor between count rate (cps) and activity concentration ($Bq \cdot kg^{-1}$), which was subsequently applied to field measurements.

5.2 Field performance test of MARK-U3 system

The field verification of the MARK-U3 system was conducted in a coastal seawater environment. Seawater samples were collected directly from the ocean at a depth of

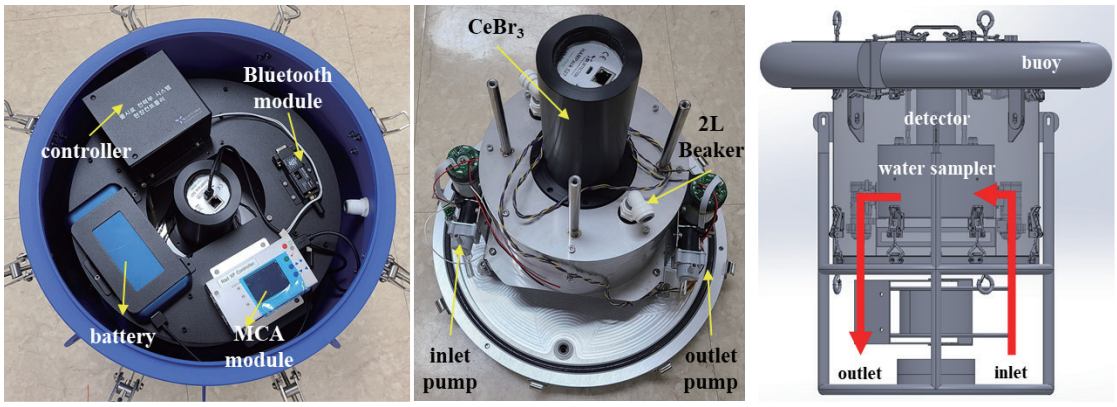

Fig. 6. (Color online) Configuration and internal water flow path of the MARK-U3 buoy-type *in situ* gamma spectrometry system.

approximately 10 m using the integrated pumping system. After the 2 L Marinelli beaker was completely filled, gamma-ray spectra were acquired for 600 s. Figure 7 shows the measured gamma-ray energy spectrum. The net count rate at 1461 keV was 0.1023 cps. By applying the Monte Carlo-derived theoretical counting efficiency, the estimated ^{40}K activity concentration was calculated to be 10.89 Bq·kg^{-1}. For validation, the ^{40}K activity concentration was independently derived from salinity measurements, yielding a value of 11.49 Bq·kg^{-1}. The relative difference between the gamma-spectrometric estimate and the salinity-based reference value was 5.2%. The reduced discrepancy compared with that obtained using the MARK-U2 system can be attributed to the improved energy resolution of the CeBr3 scintillator and the lower background level achieved through the internal sample geometry and shielding configuration. These results demonstrate that the MARK-U3 system provides accurate and stable quantitative measurements of naturally occurring radionuclides in seawater under field conditions.

6. Ship-mounted Real-time Maritime Detection System: MARK-U4

6.1 Detector configuration of MARK-U4 system

The MARK-U4 system was developed as a ship-mounted radiation monitoring detector for real-time maritime surveillance. The system employs a 2 L NaI(Tl) scintillation sensor coupled with a photomultiplier tube (SCIONIX, Netherlands), enclosed within a cylindrical MC-nylon housing to allow submerged operation (see Fig. 8). The detector is designed with a detachable mounting structure, enabling installation on the side or underside of a ship or other mobile platforms. This configuration ensures operational flexibility and mobility during maritime surveys.

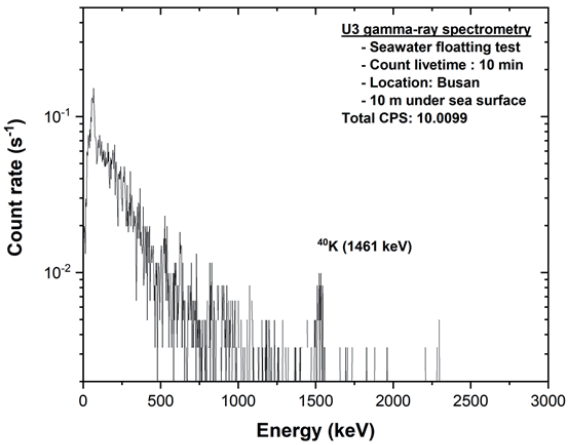

Fig. 7. *In situ* gamma-ray energy spectrum obtained with the MARK-U3 system using a seawater sample.

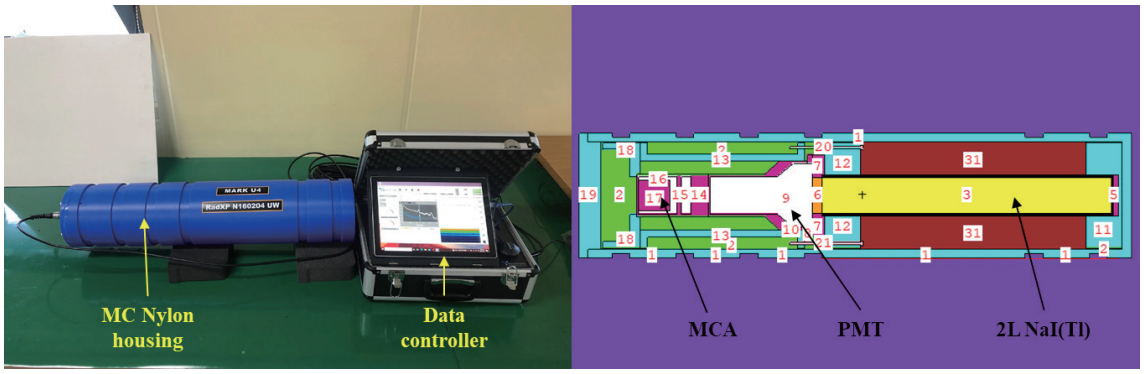

Fig. 8. (Color online) Configuration and cross-sectional schematic of the MARK-U4 system.

Spectral data are continuously acquired and processed at 2 s intervals. Each measurement is recorded together with GPS coordinates transmitted from the system control unit, enabling the real-time mapping of radiation levels. This synchronized acquisition of spectral and positional data allows the immediate identification of radionuclides via gamma-ray spectroscopy and the spatial verification of ambient dose rate distribution. To estimate the ambient dose equivalent rate from the measured energy spectrum, an energy-dependent dose conversion factor (G-factor) was derived from MCNP6 simulation. Monoenergetic gamma-ray sources covering the detector's operating energy range were simulated to calculate the corresponding detector count rates. These simulated responses were combined with the ambient dose equivalent conversion coefficients to obtain the energy-dependent G-factor, which relates the measured count rate to the ambient dose equivalent rate. The ambient dose equivalent rate was then calculated as

$$\dot{D} = \int n(E)G(E)dE, \tag{1}$$

where $\dot{D}$ is the ambient dose equivalent rate [nGy·h^{-1}], $n(E)$ is the measured count rate at energy E [cps], and $G(E)$ is the energy-dependent dose conversion factor [nGy·hr^{-1} per cps] derived from MCNP6 simulation.

6.2 Maritime radiation monitoring with MARK-U4 system

A maritime radiation monitoring experiment was conducted in a coastal sea area, using the MARK-U4 system mounted on a survey vessel. The detector was submerged in seawater during navigation, and measurements were performed continuously for approximately 4,300 s (about 1 h). For spatial analysis, the total count rate (cps) for each measurement interval was calculated for each measurement over the energy range of 50–3,000 keV. The ambient dose equivalent rate (nGy·h^{-1}) was subsequently estimated by applying the G-factor obtained from the MCNP6 simulation described in Sec. 6.1. The spatial distributions of total count rate and corresponding ambient dose equivalent rate are presented in Fig. 9. Both quantities exhibited relatively higher values near the coastline and gradually decreased with increasing distance from shore, reflecting

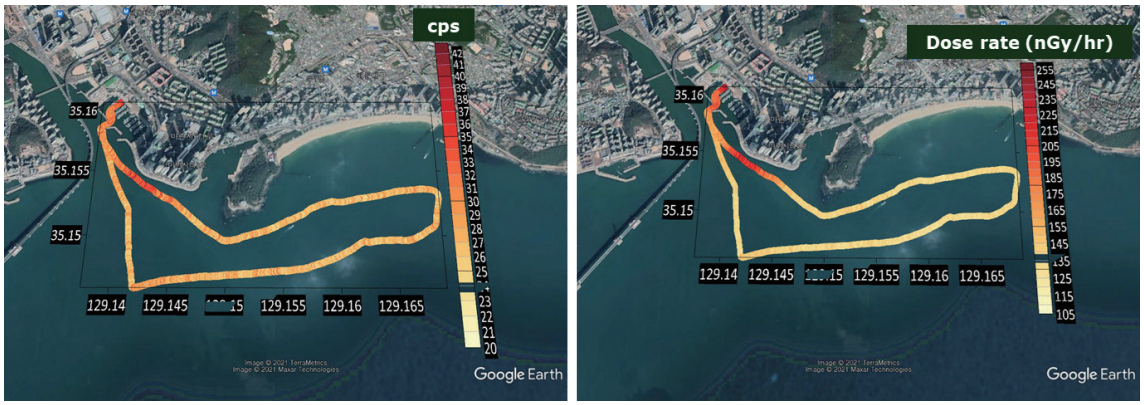

Fig. 9. (Color online) *In situ* maritime survey results obtained using the MARK-U4 system at coastal sea.

the contribution of terrestrial radiation to the marine environment. During the survey, the average ambient dose equivalent rate was 28.72 nGy·h^{-1}, while the maximum value of 53.36 nGy·h^{-1} was observed at coordinates (35.160611, 129.13923). These measured dose rates are lower than the natural background radiation level, indicating that no radiological anomalies were detected within the surveyed area.

7. Discussion

The MARK-U series was developed as a set of complementary underwater radiation sensing platforms rather than as a single universal detector. Each system was optimized for a specific measurement geometry and monitoring objective, thereby covering different layers and operational modes of aquatic radiological surveillance. In the MARK-U2 field test, the estimated activity concentration of natural ^{40}K showed a relative difference of 13.7–16.9% compared with the salinity-derived reference values. This deviation is mainly attributed to the low net count rate of the 1461 keV photopeak under natural-background conditions, where gamma rays are strongly attenuated in water and the contribution of dissolved ^{40}K to the measured spectrum is relatively small. Therefore, the uncertainty observed under ordinary seawater conditions should not be directly extrapolated to high-activity contamination scenarios. Because the relative statistical uncertainty decreases as the number of detected counts increases, a lower relative error is expected when radionuclides are present at elevated activity concentrations, provided that the detector response remains linear and spectral interferences are properly considered. The use of MC-nylon is an important design feature for underwater gamma-ray monitoring because its low density reduces the attenuation of incident gamma rays compared with metallic housings. This is particularly important for the MARK-U2 and MARK-U4 systems, where the detector measures gamma rays emitted from radionuclides distributed in the surrounding seawater. The improved radiation transmissivity of MC-nylon increases the detector response under low-count underwater conditions and is therefore essential for maintaining practical sensitivity. However, a maximum depth rating for long-term fixed deployment was not established in this study. Additional long-term immersion, pressure cycling, leakage, and biofouling tests will be required for extended or fixed-point deployment.

8. Conclusions

In this study, a series of *in situ* radiation monitoring systems (MARK-U1–U4) were developed and validated for real-time marine environmental surveillance. The systems were designed with different measurement geometries and integrated radiation sensors, enabling seabed monitoring, external seawater assessment, internal sample analysis, and ship-mounted maritime mapping. Monte Carlo-based efficiency modeling combined with field verification demonstrated strong linear correlations between measured count rates and radionuclide activity concentrations. The results confirmed that the developed sensor systems provide reliable quantitative measurements under both stationary and mobile marine conditions. Compared with conventional laboratory-based methods, the MARK-U series enables the rapid on-site analysis and real-time spatial mapping of radioactive contamination in aquatic environments. These integrated underwater radiation sensor systems offer an effective platform for environmental monitoring and emergency response in marine settings.

Acknowledgments

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References

1 J. Lee, S. H. Kim, H. Lee, H. Lee, and I. Kim: J. Mar. Sci. Eng. **10** (2022) 1541. https://doi.org/10.3390/jmse10101541
2 INTERNATIONAL ATOMIC ENERGY AGENCY: IAEA-RML-2014-02 (2015).
3 INTERNATIONAL ORGANIZATION FOR STANDARDIZATION: ISO 10703:2021 (2021).
4 C. Tsabaris, E. G. Androulakaki, and S. Alexakis: J. Mar. Sci. Eng. **11** (2023) 725. https://doi.org/10.3390/jmse11040725
5 A. Naumenko, S. Andrukhovich, V. Kabanov, D. Kabanau, Yu. Kurochkin, B. Martsynkevich, Dz. Shoukavy, and P. Shpak: Nucl. Instrum. Methods Phys. Res. A **908** (2018) 97. https://doi.org/10.1016/j.nima.2018.08.001
6 C. Tsabaris, E. G. Androulakaki, A. Prospathopoulos, S. Alexakis, G. Eleftheriou, D. L. Patiris, F. K. Pappa, and R. Vlastou: J. Env. Radioact. **204** (2019) 12. https://doi.org/10.1016/j.jenvrad.2019.04.001
7 D. Dou, Z. Zeng, W. Yu, M. Zeng, W. Men, F. Lin, and J. Li: J. Mar. Sci. Eng. **9** (2021) 721. https://doi.org/10.3390/jmse9070721
8 Y. Zhang, B. Wu, D. Liu, Y. Zhang and Y. Cheng: App. Radiat. Iso. **142** (2018) 181.
9 C. Tsabaris, C. Bagatelas, T. Dakladas, C. T. Papadopoulos, R. Vlastou, and G. T. Chronis: App. Radiat. Iso. **66** (2008) 1419.
10 C. Bagatelas, C. Tsabaris, M. Kokkoris, C. T. Papadopoulos, and R. Vlastou: Environ. Monit. Assess. **165** (2005) 159.
11 A. Naumenko, S. Andrukhovich, V. Kabanov, D. Kabanau, Y. Kurochkin, B. Martsynkevich, Dz. Shoukavy, and P. Shpak: Nucl. Instrum. Methods Phys. Res. A. **908** (2018) 97.
12 S. Lee, J. Park, J. S. Lee, H. Seo, G. B. Ko, J. M. Seo, and S. M. Kim: App. Radiat. Iso. **197** (2023) 110826. https://doi.org/10.1016/j.apradiso.2023.110826
13 G. F. Knoll: Radiation Detection and Measurement. (Wiley, Hoboken, 2010) 4th ed., Chap. 8.
14 G. Siltzovalis, V. Lagaki, I. Madesis, and T. J. Mertzimekis: App. Radiat. Iso. **226** (2025) 112206. https://doi.org/10.1016/j.apradiso.2025.112206
15 C. J. Werner: LA-UR-17-29981, Los Alamos National Laboratory (Los Alamos, NM, USA) (2017).
16 W. Ji, E. Lee, and Y.-Y. Ji: Nucl. Eng. Technol. **57** (2025) 103173. https://doi.org/10.1016/j.net.2024.08.042