

Preparation and Consideration of Sample Collection in Undeclared Areas for Denuclearization Verification

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(Received August 26, 2021 / Revised October 13, 2021 / Approved November 26, 2021)

The Republic of Korea is expected to participate in the denuclearization verification activities by the International Atomic Energy Agency (IAEA) in case any neighboring countries declared denuclearization. In this study, samples for the verification of nuclear activities in undeclared areas were selected for the denuclearization of neighboring countries, and the appropriateness of the procedures was considered. If a country with nuclear weapons declares denuclearization, it must be accompanied by the IAEA's verification regarding nuclear materials and weapons in the declared and undeclared areas. The analysis of the process samples or on-site environmental samples and the verification of undeclared nuclear facilities and materials aid in uncovering any evidence of concealment of nuclear activity in undeclared areas. Therefore, a methodology was established for effective sampling and analysis in accordance with proper procedures. Preparations for sampling in undeclared areas were undertaken for various potential scenarios, such as, the establishment of zones according to radiation dose, methods of supplying electricity, wireless communication networks, targets of sampling according to characteristics of nuclides, manned sampling method, and unmanned sampling method. Through this, procedures were established for pre- and post-site settings in preparation for hazards and limiting factors at nuclear inspection sites.

Keywords: Denuclearization, Verification, Sampling, Soil, Swipe

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1. Introduction

Many countries, including the Republic of Korea, are preventing the spread of nuclear weapons through the Nuclear Non-Proliferation Treaty (NPT) and have established the IAEA to manage nuclear materials and activities. Currently, the NPT recognizes five nuclear weapons states: The United States, the United Kingdom, China, Russia, and France, but there are also countries that are thought to have unclear weapons unofficially without actually joining or leaving the NPT. International proposals and cooperation continue to help these unofficial nuclear-armed countries declare denuclearization and carry out the denuclearization process.

If countries with nuclear weapons declare denuclearization, nuclear material production and nuclear weapons-related activities are stopped, nuclear weapons are dismantled, and related contents are verified. Verification of nuclear materials and nuclear activities will be carried out by the International Atomic Energy Agency and participating countries will be determined through international meetings. The Republic of Korea is also expected to participate in denuclearization verification activities if neighboring countries declare denuclearization.

For complete and continuous denuclearization, verification activities should proceed from the investigation of undeclared facilities and nuclear materials, as well as facilities and nuclear materials declared by the state declaring denuclearization. After discovering Iraq's secret nuclear weapons program in the early 1990s, the IAEA strengthened its safeguard system by analyzing environmental samples at reported and undeclared sites, using information on the design of facilities and types and quantities of existing materials. In particular, process samples or environmental samples collected at sites are useful for tracking nuclear activity, and make it possible to reliably identify undeclared activities [1].

Signs of nuclear activity such as reprocessing continue to be found in neighboring countries, and in addition to

disclosed nuclear facilities, secret facilities are believed to exist. Moreover, even if denuclearization is declared, there is a high possibility that some key equipment and facilities will not be declared, possibly for political reasons. Therefore, after verification of nuclear material and nuclear activity in a declared area, verification of undeclared nuclear material and nuclear activity must also be performed.

Considering past denuclearization cases, analyzing samples collected at sites and verifying contents of declarations through results is the most important part of the denuclearization verification process. In particular, information, including key factors in the denuclearization process, such as the number or quantity of reprocessing, combustion of nuclear fuel, Pu production, U concentration, and path of securing nuclear material, can be determined through ^{241}Am analysis, $^{134}\text{Cs}/^{137}\text{Cs}$ ratio analysis, and $^{240}\text{Pu}/\text{Pu}$ concentration analysis. The accuracy of these analysis methods is very high.

Accurate and effective sampling must be accompanied by proper procedures. In particular, sampling in undeclared areas involves a number of unstable factors, different from sampling in declared areas, and preparation for such factors is required.

In this study, preparations and considerations for collecting environmental samples for verification of nuclear activities in undeclared areas in the event of denuclearization situations in neighboring countries are set and examined as to whether these preparations are appropriate.

2. Classification of High-radiation Areas

Although there can be differences depending on the denuclearization scenario, verification of nuclear activities in declared regions will be carried out first when the denuclearization process begins. Later in the denuclearization process, verification of undeclared nuclear facilities and materials will be carried out. Environmental sampling in undeclared areas requires finding signs of undeclared

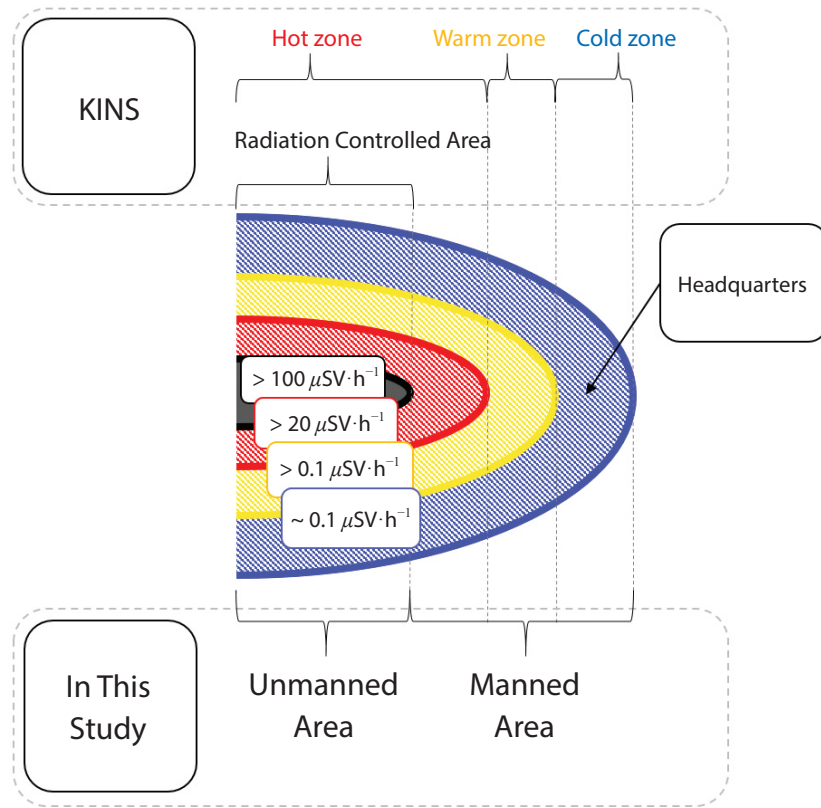


Fig 1. Area classification according to radiation dose.

nuclear activities, so there is a lack of information about areas and facilities, unlike declared areas. Therefore, extensive on-site information collection activities in the verification area should be undertaken first. Information to be collected at sites includes topography, obstructions, and the presence/absence of buildings. In particular, local radiation information is an important factor in determining radiation exposure and sampling agents of the verification team, so it should be collected with the highest priority when arriving at the verification area.

Currently, the Korea Institute of Nuclear Safety (KINS) establishes and controls zones to prevent the spread of contamination and additional victims in the event of a radiation accident where there is concern about radiation exposure and leakage of radioactive materials [2]. Dose-dependent boundaries are specifically referred to as cold zones for less

than $0.1 \mu\text{Sv}$ per hour, warm zones for $0.1 \mu\text{Sv}$ to $20 \mu\text{Sv}$ per hour, hot zones for more than $20 \mu\text{Sv}$ per hour, and radiation control zones for more than $100 \mu\text{Sv}$ per hour. A radiation control zone is an area that requires special measures to prevent radiation damage and is set as a controlled area by KINS. Hot zones are areas where the initial response can be made by fire protection services; for warm zones, public and vehicle access is restricted by the police. A cold zone is a low-level area where a field command center can be installed. In this way, each region involves a different approach.

According to the IAEA, an area measuring over $100 \mu\text{Sv}$ per hour, an area within 300 m of a spent nuclear fuel or plutonium leak, an area with a gamma/beta surface contamination measured at over $1,000 \text{ Bq}\cdot\text{cm}^{-2}$, or an area with alpha surface contamination measured at over $100 \cdot\text{cm}^{-2}$

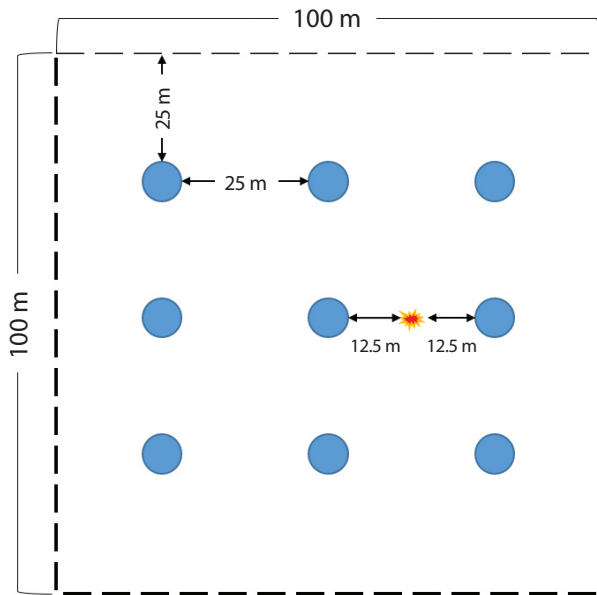


Fig 2. Assuming that evenly distributed probes in a square shape area (100 × 100 m²) and a source located in the middle between the probes.

is defined as a radiation control area and human access is not permitted [3].

In this study, based on the zone setting conditions for the leakage of radioactive materials, places where human work is possible (manned area) and places where human work is not possible (unmanned area) were divided when collecting samples. As shown in Fig. 1, the sample collection command center is installed in the cold zone of less than 0.1 μSv per hour, and the radiation dose is measured on the spot. Manned and unmanned areas are divided based on 100 μSv per hour, the boundary of the radiation management area. For example, if a subject is located at 1 m from the surface, the absorbed dose of 100 μSv·hr⁻¹ is calculated as the effect of a single point source and the radioactivity of the single point source is calculated in reverse fashion, using Formula 1.

$$H_T = \frac{\alpha \times \Gamma}{r^2} \times D \times W \quad (1)$$

H_T is the dose rate of 100 μSv·hr⁻¹ at the boundary of the management area, α is the single dotted source to

be calculated, r is 1 m, Γ is the gamma constant of ¹³⁷Cs, 0.3238 R·m²·Ci⁻¹·hr⁻¹, D and WR are the absorbed dose and radiation weight, and the product of the two is 9.73×10⁻³ Gy. Using this, the radioactivity α of the dotted line source is calculated as follows:

$$100 \times 10^{-6} = \frac{\alpha \times 0.3238}{1^2} \times 9.73 \times 10^{-3} \quad (2)$$

$$\alpha = \frac{100 \times 10^{-6} \times 1^2}{0.3238 \times 9.73 \times 10^{-3}} = 31.74 \text{ mCi} \quad (3)$$

As shown in Fig. 2, this means the radioactivity of a source under the condition that the source shows a dose rate of 100 μSv·hr⁻¹ at a distance of 1 m from the measurement point. Thus, assuming that a single point source is located on the floor in an uninhabited area, the activity of the point source can be considered to be around 31.74 mCi. Considering that the maximum allowable level of a sealed source used for calibration is 100 μCi, it can be seen that this is a very strong radiation source.

The Korea Institute of Nuclear Non-proliferation and Control (KINAC) recently developed a deployable radiation meter called a probe and is using it to evaluate local radiation dose and to detect radioactive materials. The probe is deployed (dropped) on the target area using an unmanned aerial vehicle (UAV, drone), and the radiation information obtained through the deployed probe is centrally collected and analyzed as to the exact location, intensity, and type of radiation source. These equipment and equipment operations minimize the time it takes to determine the radiation dose in the target area and provide accurate information by reducing the distance between sensors and radioactive materials.

3. Power Supply and Wireless Communication

Since an undeclared area is not mutually agreed upon, it may be inconvenient for the inspected country to disclose

the area. In addition, the undeclared area is highly likely to be a place that is not readily accessible, one that the country is using to avoid the gaze of various media such as satellite images. In this context, communication (wireless) and electrical facility infrastructure are unlikely to be sufficiently provided. Therefore, the team will of necessity prepare its own communication network and power supply methods that can be used in undeclared areas.

Several factors must be considered in advance for network construction. 1) Network construction area, usually defined by the term Network Coverage. When establishing a data network for verification of denuclearization, this is a definition of how wide a network can be physically connected to. Depending on the scope of construction, the communication method or the type or size of communication equipment may significantly change. 2) The level of power supply. Unstable and insufficient power supply causes instability of data network equipment, which makes it impossible to achieve sufficient performance. Thus, a communication method or equipment may be determined according to the type of power supplied. 3) Communication bandwidth. In general, bandwidth in communication means the data rate or frequency range of a communication system, and the bandwidth here means the data rate, or how much data can be transmitted and received while various devices are connected to the network. In general, a bandwidth of 300 kbps must be secured for video transmission, and a wider bandwidth must be secured for multiple devices to simultaneously transmit video. 4) Security. The information generated through personnel and equipment used for denuclearization requires the highest level of security. Therefore, the network must be secure so that it can secure preparation time in a fully secure or at least secure form. 5) Various equipment. Some equipment used to verify denuclearization may have been developed exclusively for verification of denuclearization, but most equipment will be multi-purpose. Since most multi-purpose equipment is likely to be developed based on communication standards, as much as possible, technologies that do not deviate from communication standards

should be applied to increase network utilization of various equipment. 6) Ease of network operation. Since there is a high possibility that personnel with low expertise in communication network construction will have to operate equipment and software in the field, it is necessary to make it easy for anyone to install and operate the network.

KINAC has built a partially decentralized wireless equipment system for equipment operation and information collection in undeclared areas and has been using it from the equipment development stage. It is based on mesh network technology, a structure that simultaneously increases the scalability and security of the network.

It is practically impossible to receive power directly from outside or build new power generation facilities because generators and transmission facilities are restricted items due to the withdrawal of the NPT. Most power generation facilities were not only built in the 1940s and 1960s but, due to limited supply and demand of parts and technologies, maintenance is not done properly, resulting in frequent shutdowns and low production efficiency. Therefore, for verification of denuclearization, the team will find it is necessary to secure its own power supply network for smooth sampling in undeclared areas. To secure electric power at a remote location, it is common to bring electricity in the form of a battery or to produce it on-site.

4. Subject and Method of Sample Collection

It is expected that sample collection from undeclared areas is unlikely to involve a smooth reaching of agreement between the denuclearization-declaring country and the nuclear activity verification team. Therefore, the time and range given for sampling are limited and re-collection may not be possible, so it is necessary to collect sufficient samples within a short time. In addition, if there are undeclared nuclear materials, the collected samples must contain nuclear materials so that they can be used to determine

signs of nuclear activity. To this end, the items to be prepared when collecting samples were examined and set up.

Environmental samples give clues or evidence that is capable of showing traces of leaked nuclear material based on the possibility of a major substance leaking out of the process [4]. Radioactive material leaked to the outside accumulates on the walls of buildings, such as outside windows, near doors, or on chimneys; it also accumulates in the surrounding environment, such as in the soil, plants, and objects. Therefore, samples containing nuclear material can be directly collected from such areas and items.

A soil sample is a representative sample that can verify nuclear activity because radioactive material released from nuclear activity accumulates on the ground near buildings. The nuclear material is adsorbed into the soil and exists in soil for a long period of time, depending on the properties of the material such as the adsorption and solubility of the particles [5]. Depending on the characteristics of the target nuclide to be collected, soil samples by surface layer or depth may be targeted. Therefore, soil samples are often used for monitoring the environment around nuclear facilities [6].

Swipe samples were developed to identify information such as uranium spectra in a facility; they are obtained by wiping items and analyzing the fabric. They were started to replace conventional sample collection methods that are not possible at nearly-destroyed sites in Iraq in the 1990s [7]. To verify nuclear activity, swipe samples can be collected by wiping with a cloth the part of the building where nuclear material may have leaked, such as door frames, windows, and chimneys, or surrounding objects such as plants, where leaked nuclear materials may have accumulated. Therefore, samples collected in undeclared areas can be soil and swipes collected in the surrounding environment of the undeclared area.

In addition, through radiation dose evaluation, manned and unmanned sampling methods are classified based on the area decided on. If the radiation control area is not directly accessible to humans, samples can be collected using unmanned aerial vehicles.

4.1 Soil Samples

For soil samples, the depth at which they are to be collected is set according to the object or purpose of collection. The greater the depth of the required samples, the greater the number of samples, the higher the cost, and the more time it will take for samples to be obtained. Therefore, an appropriate depth should be selected. Since sampling in an undeclared area has the purpose of collecting a sample containing the target nuclear material within a limited time, it is considered that methods involving deeper collection depth are not suitable. Radionuclide distribution in the soil may vary depending on the physical and chemical properties of radionuclides, precipitation, soil algae, and climatic conditions. Highly mobile substances move with water to depths of 1 m or are absorbed by plants through their roots. However, most radioactive materials are well absorbed or adsorbed by soil particles, so their mobility is low [5].

In the Chernobyl nuclear power plant, ^{90}Sr , ^{147}Cs , ^{154}Eu , ^{155}Eu , ^{238}Pu , ^{239}Pu , ^{240}Pu , and ^{241}Am were investigated. In addition, in several investigations about materials release during the reprocessing operation, ^{129}I , ^{134}Cs , and ^{106}Ru were found [13-14]. As a result, it was confirmed that more than 80% of nuclides remained in the surface soil 30 years after the accident [8]. In particular, it was found that 40–50% of ^{90}Sr be migrated to 5 cm below the surface and more than 70% be migrated to 10 cm below the surface in soil with specific conditions [8]. Also, in a study to understand the vertical distribution of radioactive materials in the soil, 96% of ^{134}Cs and ^{137}Cs , and 100% of ^{131}I were found within 5 cm of the surface layer [9]. In the case of $^{239+240}\text{Pu}$, more than 60% of $^{239+240}\text{Pu}$ existed in soil up to a depth of 5 cm and about 90% of $^{239+240}\text{Pu}$ existed up to a depth of 10 cm [15].

Based on these research results, it is believed that nuclear materials exist in the soil within 5 cm of the surface layer, including radioactive cesium, which is the main target of analysis. In particular, since the surface soil is most directly and superficially exposed to nuclear material and adsorbs particles, surface soil must be sampled. In the



Fig 3. Core sampler for soil sampling.

Chernobyl accident, a sharp edge ring was used to collect soil by inserting it into the soil surface on the one sharp side [5]. Even in the case of the Fukushima nuclear accident, when collecting soil samples to monitor the contamination of the surrounding soil, as shown in Fig. 3, a stainless steel cylindrical core with a sharp cross-section was attached to the Core Sampler and samples of 100 mL were collected [10]. Therefore, it is expected that the core sampler shown in Fig. 3 can be selected and used as a soil sampling tool for verification of nuclear activity. This sampler can provide a suitable range of 100 ml volume samples to a depth of 5 cm; teams will use a separate stainless steel core at each sampling point to prevent cross-contamination. In addition, by attaching lids on the upper and lower parts, making it easy to seal and transport, the core can be used not only as a sample collection tool but also as a container for storing and moving samples. The core sampler, which is the main body, has a height of about 20 cm, which is considered appropriate because it involves only a slight burden to collect and move the sample.

4.2 Swipe Sample

There are two types of swipe kits for sample collection: a cloth (cotton) swipe for wiping facilities and objects, and a swipe for collecting a sample inside a hot cell. In the cotton swipe, the sampler collects directly from the outside of the hot cell, but the hot-cell swipe collects the sample inside the hot cell through remote control [11]. In the case of

an undeclared area, which is the purpose of this study, the swipe kit for hot cells is not suitable because there is a high probability that major nuclear materials or major activities such as hot cells were processed and hidden in advance, even if nuclear facilities remain. Therefore, we intend to use a cotton swipe kit, which can be used in the environment around a building, for such things as nuclear material, objects, or plants that have absorbed radioactive materials leaked from inside and outside the building. These kits must be manufactured in a cleanroom laboratory, inspected for contamination, sealed, and transported to the sampling site. Cotton swipe kit components include latex gloves, 6–10 swipe sides, zip-lock bags of different sizes for double closure, seals, aluminum foil, and a sampling log [7]. In conclusion, the swipe method is useful because the extraction process is not difficult, elements are lightweight and easy to move, and various analyses can be adopted when nuclear material is collected by swiping the same surface of an object to be harvested several times.

4.3 Unmanned Sample Collection

If the undeclared area is set as a radiation control area, and cannot be directly accessed by humans radiation dose evaluation, while nuclear activity in the area is suspected, samples must be collected. In such a situation, samples can be collected using unmanned equipment on behalf of the human collector. Since the beginning of nuclear assessment, unmanned ground vehicles have been used in areas difficult for humans to directly access, such as nuclear power plant accident sites or dismantled nuclear facilities.

Similar to manned sampling, there are design elements that must be installed at a minimum for an unmanned vehicle to collect samples. 1) Stable operation should be possible in high-radiation conditions. The basic reason for the operation of unmanned ground vehicles is that the radiation dose in the mission area is high, and high radiation levels can have various effects on not only people but also equipment, causing malfunctions. Therefore, it is necessary to

prepare a shielding aspect in consideration of the radiation level expected in the operational area. 2) It is important to apply an appropriate energy source that affects the operating time of the equipment. It is difficult to determine exactly how long tasks will be performed in advance; however, in general, movement speed is slow compared to humans, and distances to move are not short. So, the task execution time might be longer than expected. Therefore, various methods should be sought to supply sufficient energy for long periods. 3) Communication is an essential element for the operation of unmanned equipment, along with energy supply, and it is necessary to secure the main communication channel and an auxiliary communication channel to enable smooth communication during long-distance work. 4) Transportation capacity (Payload). Because it is a device that collects samples, it must be moved while collecting a large number of samples, and since it must be operated in a high-radiation situation, shielding against radiation is essential. Therefore, since basic shielding must be applied, there is a possibility that the weight of the equipment itself will increase significantly. Therefore, it is necessary to secure a design margin for the transport capacity so that device can operate well even in situations where large weight applies.

5. Practical Considerations

In the event of a denuclearization situation, not only the aforementioned technical problems but also various practical limitations may arise. This section examines the factors that the Republic of Korea should consider through geographical and political relations with the current denuclearization target country.

5.1 Local Language

In the process of closely analyzing the site of an undeclared area for sample collection, obtaining relevant information from local residents or obtaining direct information

through dialogue with the person in charge of inspection can be considered a very effective inspection method. In particular, when conducting an inspection in a non-English speaking country, it can be very important to have a person assigned to the inspection team who directly understands the language of the country. Therefore, for the denuclearization of the Korean Peninsula, personnel who know Korean and understand Korean culture must be included in the inspection team.

5.2 Collection Time

The act of taking a sample can be seen as a simple task that can be completed in a few hours. However, in the actual sampling process, various procedures need to be considered and prepared for the collection, requiring several hours at the site; these include radiation dose, collection amount setting, collection material, collection methodology, etc. In addition, if necessary, additional sampling may be required depending on the results of the onsite analysis.

In particular, in cases of sampling in an undeclared area, the time for sample collection may be extremely limited or the sample collection itself may be refused because it is an operation outside the declared area. Therefore, for effective sampling, efforts should be made to achieve successful sampling in the shortest possible time by simplifying the sampling procedure, developing dedicated equipment, and optimizing the device. Although there will be differences depending on whether and how to negotiate, there may be cases in which short time sampling within 24 hours will be required, and it will be necessary to set up a scenario or establish a procedure for this short time.

5.3 Sample Transport and Management

Collected samples can be largely divided into soil samples, radioactive materials, and swipe samples, as detailed above. In the case of soil samples, since they are brought into South Korea from abroad, quarantine is essential, and

Table 1. Importance of considerations

List of considerations	Importance High	Importance Middle	Importance Low
Classification of high-radiation area	○		
Power supply		○	
Wireless communication		○	
Soil sampling	○		
Swipe sampling	○		
Unmanned sampling			○
Local language		○	
Maximum collection time		○	
Sample transport and management			○

* Criteria for classification of importance are based on IAEA TECDOC 486, and research results from IAEA.

professional management is required so that microorganisms, plant seeds, and pests do not become problems during the storage and disposal of samples. In addition, considering the specificity of samples for nuclear inspection, the continuity of knowledge (CoK) of the sample must be secured, and special attention must be paid to prevent problems such as deodorization and damage.

It may be difficult to bring in collected high-level radioactive material because relevant laws of South Korea. Moreover, specialized facilities such as hot cells are required for storage and processing even after importation. In South Korea, KINS and KAERI have representative hot cell facilities, but actual storage may be difficult due to the specificity of samples and security-related issues.

Samples collected can be small in amount, but may contain nuclear material such as ^{235}U or Pu. In addition, if it is verified that there is nuclear material, a declaration and control procedure is required so that quantities can be measured by the IAEA and KINAC.

6. Conclusion

For denuclearization situations of neighboring coun-

tries, preparations were made and appropriate measures selected for sample collection for verification of nuclear activity in undeclared areas. Verification of undeclared nuclear facilities and nuclear materials is the latter part of the denuclearization stage and serves as the final verification related to nuclear activities [12]. Therefore, it is necessary to prepare measures for sampling in undeclared areas, and to continuously check whether these measures are appropriate.

Through this study, to collect samples in undeclared areas, matters such as setting of zones according to radiation dose, manned sampling tools, and requirements for unmanned vehicle sampling were established. If an area with a radiation dose of $100 \mu\text{Sv}\cdot\text{hr}^{-1}$ or higher is identified, it is assumed that there was undeclared nuclear activity and area shall be set as a radiation management area. Collected samples shall be soil samples and swipe samples, which are expected to contain information on the history, process, etc., of nuclear activities. When samples were directly collected by a human team, it was found appropriate to use a core sampler capable of collecting surface soil 5 cm away from the surface and a cloth managed by a clean laboratory for swipe samples. These factors are the main factors that determine the direction of harvesting for the safety of the

harvester, so they should be set first.

In this study, we considered 1) classification of high-radiation areas, 2) power supply and wireless communication, 3) sampling methods for soil, swipes, and unmanned sampling, 4) the local language, 5) the collection time, and 6) sample transport and management. If possible, all these factors should be considered before entering an undeclared area. However, if these preparations are not sufficient, we can further prepare for a situation by considering the following items of importance (Table 1).

However, because unpredictable contingencies exist or situations can occur in undeclared areas, factors that may vary from situation to situation should also be identified based on the conditions established in this study. Afterwards, preparations and requirements will be studied so that not only the collection of samples but also their pre-treatment and cross-analysis can be performed according to the individual collection processes. Moreover, the warm zone between $0.1\text{--}20\ \mu\text{Sv}\cdot\text{hr}^{-1}$ will be considered to adapt a new subdivided sampling method. Based on this, it is believed that the government will be able to complete a preliminary manual to prepare for verification of nuclear activities in undeclared areas during denuclearization situations.

Acknowledgements

This work was supported by the Nuclear Safety Research Program through the Korea Foundation Of Nuclear Safety (KoFONS), using financial resources granted by the Nuclear Safety and Security Commission (NSSC) of the Republic of Korea (No.1905010).

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