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Study on the Experiences of Subsurface Soil Remediation at Commercial Nuclear Power Plants in the United States

미국 원전의 심층토양 제염사례 연구

Hyoung-Woo Lee, Ju-Youl Kim, and Chang-Lak Kim*
KEPCO International Nuclear Graduate School, 658-91, Haemaji-ro, Seosaeng-myeon, Ulju-gun, Ulsan, Republic of Korea

이형우, 김주열, 김창락*
한국전력국제원자력대학원대학교, 울산광역시 울주군 서생면 해맞이로 658-91

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Regulatory agency and licensee are preparing for the site restoration of Kori unit 1, the first commercial NPP in Korea, scheduled for 2031. Developing regulatory guidelines and strategies is essential for effective restoration work. Unfortunately, Korea does not have experience of site restoration of commercial NPPs. Therefore, it is important to review cases from experienced countries to establish a strategy and regulatory standards. The U.S. has had numerous soil remediation experiences using RESRAD and MARSSIM. However, formalized evaluation methodologies for subsurface soil have not yet been established in MARSSIM. This survey focused on subsurface soil remediation by reviewing the five decommissioned NPPs under regulation of the US NRC. Overall process of remediating a contaminated subsurface soil and groundwater was reviewed to identify considerations and lessons that could be applicable in Korea. In addition, an applied methodology for evaluation of contaminated subsurface soil and related major issues between regulatory agency and licensees were reviewed in detail to support establishment of remediation strategy for Kori unit 1.

Keywords: Site restoration, Soil remediation, Subsurface soil, RESRAD, MARSSIM

*Corresponding Author.
Chang-Lak Kim, KEPCO International Nuclear Graduate School, E-mail: clkim@kings.ac.kr, Tel: +82-52-712-7333

ORCID

Hyoung-Woo Lee	http://orcid.org/0000-0002-9803-9549	Ju-Youl Kim	http://orcid.org/0000-0003-4076-0760
Chang-Lak Kim	http://orcid.org/0000-0002-6931-9541		

2017년 고리 1호기 영구정지 이후 규제기관과 원전운영자는 2031년으로 예정된 부지 제염 및 복원을 수행하기 위해 사전준비 작업을 진행해오고 있다. 적절한 계획 수립 및 효과적인 규제활동을 위해서 규제지침 개발과 기술적 근거수립이 무엇보다 선행되어야 한다. 국내에선 연구용 원자로 해체경험이 있지만 상업용 원전은 없기 때문에 해외 해체 선도국의 부지복원 사례연구를 통해 토양 제염과 관련한 기술사항 및 규제기준에 대한 정보를 제공한다면 고리 1호기 복원계획 및 규제기준 수립에 효과적일 것이다. 미국은 상업용 원전에 대한 다양한 해체경험을 축적해 왔으며 RESRAD 프로그램 및 MARSSIM 절차와 같은 체계를 개발 · 적용하여 오염된 부지의 조사, 제염, 복원 및 해제를 통합적으로 수행하고 있다. 이 논문에서는 미국의 5개 상업용 원전(해체완료 4개, 지연해체 1개)을 대상으로 심층 토양오염에 대한 부지복원 사례연구를 수행하였다. 심층토양의 경우 표층토양과 달리 미국에서도 정형화된 평가방법론이 아직 정립되어 있지 않았고, 오염평가시 지하수 영향을 고려해야 하는 특성이 있음이 확인되었다. 따라서 향후 고리 1호기 부지복원 전략수립 및 규제지침 개발에 고려할 만한 제안사항을 도출하고자 기술 및 규제 관점에서 심층토양에 대한 오염평가, 제염기준 수립, 제염작업 수행 및 결과 검증까지 단계별 주요사례를 정리하고, 미국 해체사업자가 적용한 심층토양 평가방법과 규제기관과 해체사업자 간에 논의된 주요 쟁점사항을 분석하여 시사점을 도출하였다.

중심단어: 부지복원, 토양제염, 심층토양, RASRAD, MARSSIM

1. Introduction

The regulatory body is performing a preliminary study to establish the regulatory guidelines for the Decontamination and Decommissioning (D&D) of Kori unit 1 - the first commercial Nuclear Power Plant (NPP) since 2017. Korea Hydro and Nuclear Power Co. decided the immediate dismantling (DECON) option for Kori unit 1 and established the site restoration schedule starting in 2031 for 2 years. Some countries have experienced site restoration of shutdown reactors. Especially, the U.S. has soil remediation experience with commercial NPP sites (8 sites) [1]. This survey focused on the U.S. experience in order to share the lessons learned by reviewing technical and regulatory criteria applied in their site restoration works.

Site remediation is the final stage of decommissioning before the release of the NPP site for its intended purpose such as unrestricted or restricted use. It is necessary to verify remediation results of the site to protect the health and safety of the intended target from radiological hazards based on their purpose. The intended target is a group of people that will use the released site after remediation and will be expected to receive the maximum exposure from the residual radioactivity. This group is referred to as 'critical group' and has two types. One group is the resident farmer in using the site classified for unrestricted use, commonly referred to as 'greenfield'. The other group is the industrial worker using the site classified for restricted use, commonly referred to as 'brownfield'.

As part of remediation procedures, it should be verified that residual radioactivity levels in the media (soil, water, etc.), which are reduced by performing site remediation work, do not exceed the maximum target value referred to as Total Effective Dose Equivalent (TEDE). TEDE is a risk-based regulatory standard considering internal and external exposures. The US NRC sets a TEDE limit such as 0.25 $mSv \cdot yr^{-1}$ for the critical group for unrestricted use in the 10 CFR Part 20. 1402 or 1 $mSv \cdot yr^{-1}$ for restricted use that is acceptable by satisfying the ALARA (As Low As Reasonably Achievable) principle in the 10 CFR Part 20. 1403. In general, total residual radioactivity level from all exposure pathways (direct exposure, inhalations, and ingestions) in the site shall meet the unrestricted use criterion after remediation work.

A remediation plan for radiologically contaminated media can be established by analyzing the radioactive level of each media based on the scenario and the criterion. Each media has different exposure pathways and is then subdivided into the release criteria referred to as Derived Concentration Guideline Levels (DCGLs) for the development of remediation plan and verification of its results. DCGLs are derived by the RESRAD (RESidual RADioactive materials) computer code using a result of an initial site assessment data and further characterization survey data for the site.

The RESRAD code is mainly used to calculate effects of contaminated soil with radioactive materials (total 91 radionuclides) to an intended target by simulating the movement of contaminants in the air, water, and biological media using site-specific parameters. The RESRAD code has nine exposure pathways : direct exposure, inhalation of particulates and radon gas, ingestion of plant foods, meat, milk, aquatic foods, water, and soil. The soil and water transportation pathways are the most important factors for analyzing the potential impact on a single receptor that is to be received the maximum exposure in a critical group [2].

In addition, the MARSSIM (Multi-Agency Radiation Survey and Site Investigation Manual) process was developed as a guideline for a comprehensive decision framework of site remediation and restoration work. MARSSIM includes methodologies about planning, implementation, evaluation, and documentation of the surface soil remediation that can be supported by the RESRAD modeling. In particular, MARSSIM provides a standardized and consistent approach to Final Status Survey (FSS) after remediation work to ensure compliance with site release criterion such as 0.25 $mSv \cdot yr^{-1}$ for unrestricted use. FSS is a procedure using statistical tests that demonstrates whether remediation results meet the site release criterion or not [3].

The soil is divided into two categories as defined in the 40 CFR 192.32 and the 10 CFR 40 Appendix A as surface soil which is up to 15 cm in depth and subsurface soil which is below 15 cm depth and down to an aquifer. The subsurface soil is also referred to as deep soil in some plants [3-5]. It is important to distinguish the soil types because each type of soil has a different exposure scenarios and pathways based on their unique assumptions. For example, it is reasonably expected that the typical agricultural activities by resident farmers such as (e.g. hoeing, plowing) may disturb the surface soil in a released site. Therefore, the effects of residual radioactivity in the surface soil should be considered in combination with associated exposure pathways with the surface soil. The other hand, subsurface soil is less likely to be contaminated due to its depth. However, if the subsurface soil is contaminated, groundwater is also assumed to be contaminated which required a comprehensive assessment for an evaluation of potential safety considering the migration of contaminants. The U.S. NRC places an emphasis on a consideration of subsurface soil and groundwater contaminations from the beginning of the remediation process.

RESRAD is able to analyze the effect of contaminated soil with various geohydrology parameters regardless of its depth while MARSSIM provides a formalized process for a surface soil only. The measurement methods applied to the MARSSIM process are a scan survey, direct measurement, and sampling. However, these techniques are restricted to the subsurface soil due to a technical limitation, data uncertainty, and economic efficiency [6-7]. For this reason, the formal guideline for a subsurface soil is not available and only be evaluated on a case-by-case basis in the U.S.

RESRAD and MARSSIM has been applied in D&D projects in Korea for non-commercial reactor sites such as Korea Research Reactors (KRR-1 and 2) in 1997 [8] and Uranium Conversion Plant (UCP), a raw material processing facility of the CANDU (CANada Deuterium Uranium) type reactor fuel in 2004 [9].

The five commercial NPP sites in the U.S. (Big Rock Point, Dresden, Haddam Neck Plant, Maine Yankee, and Rancho Seco) were selected to survey their remediation experience for a subsurface soil by reviewing relevant documents submitted by each NPP site under 10 CFR 50.82. (See Table 1)

2. Soil Remediation Process in the U.S.

The main steps of an overall site remediation process in the U.S. are shown in Fig. 1.

The translation process is to convert release criteria into corresponding site-specific DCGLs for each radionuclide of concern using the RESRAD modeling. Some exposure pathways in scenarios could be excluded based on a site-specific condition and measurement data. However, it is recommended to decide DCGLs with a conservative approach for the safety of the general public and environment. The measurement procedure is to obtain site-specific data by field or laboratory measurement techniques during HSA and the characterization survey. The decision procedure provides confidence to verify compliance of data obtained from FSS by applying decision rules with statistical tests in the MARSSIM guideline. Preliminary data obtained by an individual process to be qualified through the iteration process by verification and validation procedures referred to as the Data Quality Objectives (DQO) in MARSSIM.

An overall remediation process for a surface soil and a brief guidance for the subsurface soil guided in NUREG-1757, Appendix G in volume 2 are summarized in Fig. 2 [3-4].

If the HSA data indicates a significant amount of residual radioactivity in the area, it should be classified as an impact zone for a detailed survey later. A licensee sets a final site release criterion based on a survey data from HSA. The NRC site release criteria and the stakeholder requirements should be considered before making a decision. The decided criterion is subdivided into radionuclide levels in each media through the established scenarios and models in the RESRAD code. A licensee will obtain certain DCGL levels in each media such as subsurface soil and groundwater for a radionuclide basis. The characterization survey can provide precise data about the impact zone by a systematic survey used for the RESRAD modeling, remediation planning, and FSS. Then, the survey results are compared with DCGLs to determine whether immediate remediation can be started or more survey is required. After that, a selection of remediation methods such as excavation and dewatering can be made based on the previous results. An appropriate procedure for radiation protection and a waste disposal plan are necessary for remediation works. FSS is a critical process for persuading regulatory agencies (US NRC, EPA, etc.) and stakeholders to release a site. It starts with the classification of contaminated areas (Class 1, 2, 3) and defining the Survey Units (SU) for a confirmation survey after remediation. Accurate technical criteria should also be established to demonstrate compliance with the site release criteria, such as the level of MDC (Minimum Detectable Concentration) and the level of site scanning and sampling requirements to be used as a basis for statistical analysis.

NUREG-1757 guides overall remediation activities and every process except the RESRAD modeling is a part of MARSSIM. The MARSSIM process has two assumptions for subsurface soil. The first assumption is that when excavation work is performed, the mixing of radioactive materials in the subsurface soil is inevitable. In addition, the amount of soils with high level of contaminants exceeding release criteria are homogeneously mixed when it is brought to the surface. Therefore, an average concentration for an excavated soil volume is applied to surface soil. It will affect exposure pathway scenarios for a surface soil in the RESRAD modeling by increasing an exposure dose to an intended target. The second assumption is the radionuclides in a subsurface soil will migrate to the groundwater. Therefore, the total inventory of residual radioactivity in a subsurface soil impacts a groundwater exposure pathway and modeling by RESRAD [3].

When appropriate DCGLs are established and detailed contamination data for a subsurface soil are collected, a core sampling survey is required, not to exceed 1-meter depth in each sediment, for an evaluation of residual radioactivity in a subsurface soil due to a limit of current scanning technology. In this case, applying average concentrations of radionuclides over the volume or the thickness to the contaminated soil are prohibited because a discrete nature of contamination

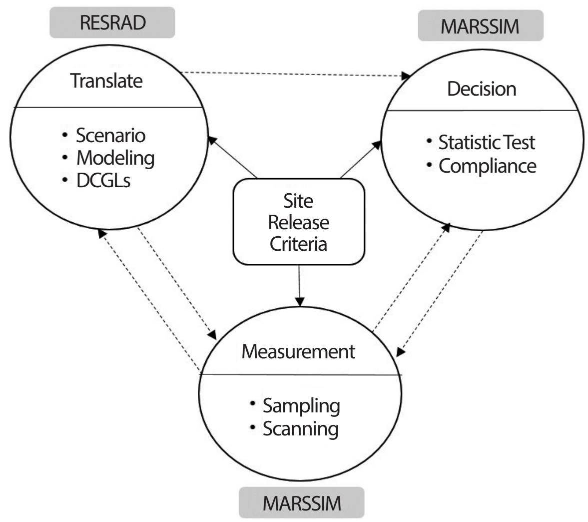

Fig. 1. Concept of Site Remediation Process.

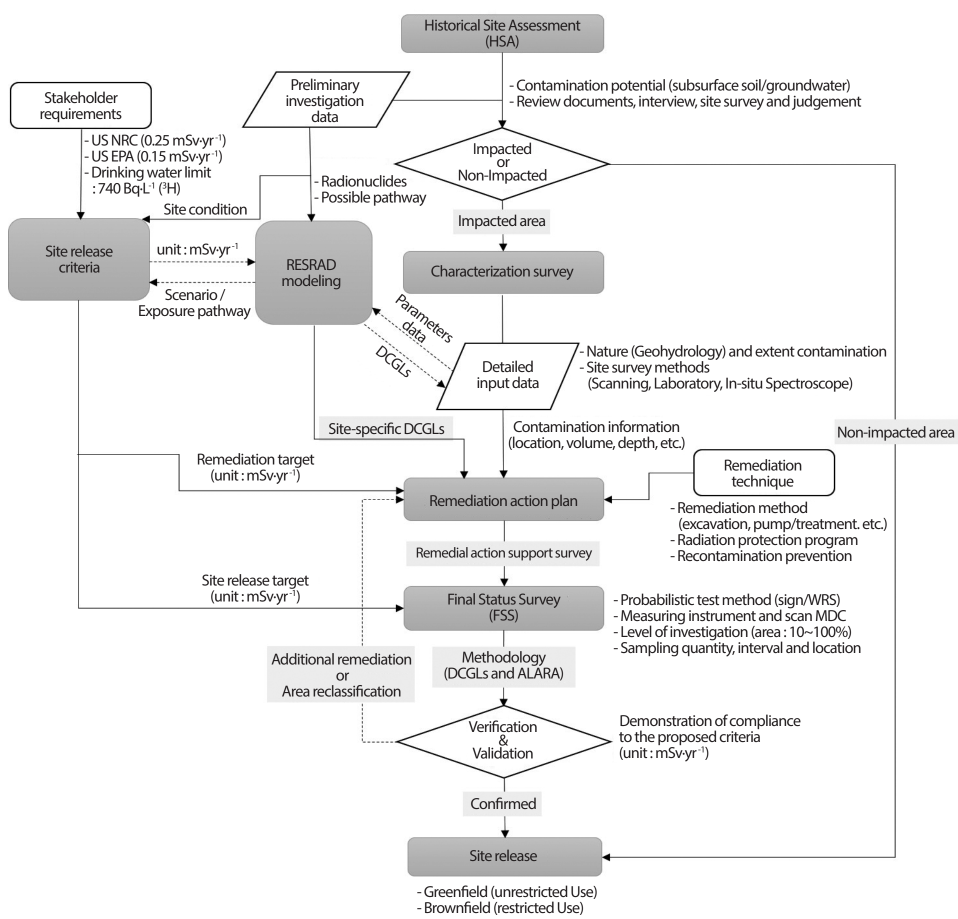

Fig. 2. Flowchart Describing Site Remediation Process.

Table 1. Decommissioning Status of Commercial NPP Sites in the U.S.

NPP	Type	Capacity (MWe)	Operation/Shutdown	D&D Finished	Status	Site Usage
Big Rock Point (BRP)	BWR	67	1964/1997	2007	DECON Completed	ISFSI
Haddam Neck Plant (HNP)	PWR	560	1974/1996	2008	DECON Completed	ISFSI
Dresden Unit 1	BWR	700	1959/1978	(2036)	SAFSTOR	ISFSI
Maine Yankee (MY)	PWR	860	1973/1996	2005	DECON Completed	ISFSI
Rancho Seco (RSNGS)	PWR	918	1974/1989	2009	DECON Completed	ISFSI

and an elevated level of radioactivity in a small area referred as hot spot is commonly reported in many sites.

3. Soil Remediation Experience of NPP sites in the U.S.

The site-specific remediation experience for a contaminated subsurface soil can be found in project documents submitted by each plant such as the Post-Shutdown Decommissioning Activities Report (PSDAR), License Termination Plan (LTP) and FSS in accordance with 10 CFR 50.82. The plant shall continuously update LTP to reflect any changes during the entire period of D&D project in accordance with 10 CFR 50.71. Additional documents were also reviewed such as the D&D experience report of Connecticut Yankee NPP [10] and the groundwater tritium investigation report in Dresden NPP [11].

HSA and site characterization survey provide essential information for the development of site-specific soil conceptual model and DCGL calculation input data. Then, remediation planning and FSS are followed based on a release criterion. Unfortunately, formal guidelines for subsurface soil are not provided by the US NRC due to several reasons : exposure mechanisms of surface soil are unclear; access is limited; exhaustive scanning is too costly; and the vadose zone is usually inhomogeneous [12].

The most significant subsurface soil remediation cases are summarized based on the MARSSIM process including a contaminated area and status, remediation process and implementation and its result for each plant as shown in Table 2. An overall remediation process of subsurface soil is organized from the development of appropriate DCGL to an application of evaluation methods. Furthermore, assumptions, procedures, and results accepted by the US NRC are also stated.

3.1 Big Rock Point (BRP)

A significant groundwater contamination occurred due to a leakage of steam condensate (75.7 m^3) from a buried pipe connected to the Condensate Storage Tank (CST) in 1984. The remediation activities were completed as of 2005, but tritiated water remained beneath the Turbine Building (TB) foundation.

The core sampling results of the contaminated soil (150 m^3) in TB foundation showed that residual radioactivity was limited to a 30 cm depth compared with site-specific DCGLs. However, a demolition work of TB and Compound Building (CB) foundation (30,000 m^3) required an excavation (total 1,776 m^2) of subsurface soil up to 4 m and substructure up to 10.7 m in depth.

It was found that shallow and intermediate groundwater zones were interrupted during excavation process of subsurface soil. Consequently, a comprehensive dewatering system was installed including slurry walls to maintain an excavated area in a dry condition. Isolation of the excavation area from groundwater intrusion was important to minimize radiation exposure to workers. The collected groundwater was pumped out to a retention basin for a sediment collection and released under discharge regulations such as the Offsite Dose Calculation Manual (ODCM) in the site [17].

The plant set a site release criterion as 0.25 mSv·yr^{-1} with a modified resident farmer scenario, excluded the meat and milk intake routes reflecting geographic characteristics of the site. A site-specific DCGL was conservatively derived for subsurface soil and groundwater considering ^{3}H [16].

As a result of HSA, only 0.1 km^2 of the industrial area was identified as an impact area and Turbine Building (TB) and Containment Structure (CS) areas were classified as Class 1, the most significantly contaminated area. 100% of surface soil was scanned in this area with the NaI (sodium iodide scintillator) detector and several samples were collected according to sign test requirements in MARSSIM.

The site-specific DCGL of ^{60}Co was determined as 0.119 Bq·g^{-1} for soil. After a remediation work, FSS was performed under the assumption that all residual radioactivity in soil was attributed from a ^{60}Co. Finally, it was confirmed that total residual radioactivity in the site was less than the proposed limit (0.185 Bq·g^{-1}) in LTP [16].

3.2 Haddam Neck Plant (HNP or Connecticut Yankee)

A different radionuclide was detected in Radiological Control Area (RCA) and adjacent soil including ^{90}Sr in the storage tank near CB as a result of HSA. The plant implemented a graded approach for the classification of subsurface soil as Class A (high), B (medium), and C (low) and about 5% (101,000 m^2) of areas were classified as a target for a remediation planning [18].

Stakeholder requirements such as the US NRC, US EPA and the State of Connecticut were comprehensively reviewed to decide the site release criteria. The plant and stakeholders were agreed to apply the resident farmer scenario with unrestricted use and set the criterion as 0.15 mSv·yr^{-1} for soil while total criterion was 0.18 mSv·yr^{-1} including 0.04 mSv·yr^{-1} for groundwater.

The Primary Auxiliary Building (PAB) area was classified as Class 1 and then a remediation work was performed up to 12.2 m in depth in a contaminated subsurface area including a bedrock using an excavators and a high flow rate vacuum trucks until a residual radioactivity level was reached below a screening DCGL adjusted to 0.1 mSv·yr^{-1} [10].

DCGL for soil was developed for surface and subsurface separately for FSS. The core boring survey was performed for the subsurface soil to a depth of 3 m in each 1 m length and a sampling quantity was calculated according to MARSSIM. Finally, the plant satisfied the site release criterion and released as a result of FSS [10].

The US NRC asked to verify the applicability of a biased sampling analysis method based on expert judgment for subsurface soil suggested in LTP. The plant responded that the collected data was verified through the Data Quality Objectives (DQO) process according to MARSSIM [19].

3.3 Dresden Unit 1

Among three Dresden NPP units, the first unit was put into deferred dismantling (SAFSTOR) until 2027. A site restoration work was scheduled to commence together with unit 2 and 3 starting from 2035. Tritium leakage (226,810 Bq·L^{-1}) was indicated in 2004 at the Condensate Storage Tank (CST) in unit 1 next to CB in unit 2 and 3. The leakage was suspected from a penetrated buried pipe between the High-Pressure Injection System (HPIS) and the CST due to a degradation of the moisture barrier wrapping, as well as a deficiency of the cathodic protection system. Approximately 2.4 million liters of tritiated water (8.547×10^{12} Bq) was released in one year. After a replacement of the corroded pipe (approximately 61 m long) with the excavation of adjacent subsurface soil, the monitoring wells were installed to check the groundwater characteristics and the tritium migration evaluation. The evaluation results showed that migrated contaminants did not affect the public and the environment. Therefore, a decision was made for surveillance activities without additional remediation [11, 20].

Two major regulatory issues arose from the US NRC and the Illinois state EPA. First, the plant requested NRC to permit on-site disposal of a slightly contaminated soil (about 6,000 m^3) that was below the site release criteria for unrestricted use in accordance with 10 CFR 20.2002. NRC requested for additional information regarding analyzation of contaminants and evaluation of the potential impact. NRC subsequently approved the request with the addition of an engineered barrier and a surficial aquifer monitoring around the on-site disposal area [21]. Second, the Illinois state EPA issued a violation notice to the plant after an indication of unauthorized releases of contaminated groundwater in November 2005 and May 2006. The contaminated water was produced as a result of a tritium leak remediation and was released through a drainage channel instead of a designated discharge route. The plant responded that the groundwater produced during a soil excavation was processed through the radioactive waste system in Dresden NPP and was discharged in accordance with the submitted groundwater tritium investigation report to EPA. In addition, groundwater discharge was not required a pre-authorization from EPA [22].

3.4 Maine Yankee

The significant soil contaminations and leaks were found at a flange connection in the Refueling Water Storage Tank (RWST) as a result of HSA in 1988. A further sampling analysis during a site characterization survey identified three major contaminated areas : RWST, Processed Primary Water Storage Tank (PWST) and Shielded Radiological Waste Storage Area (SRWSA) in the Radiologically Restricted Area (RRA). A remediation work for a subsurface soil was performed in those areas after an analysis of contamination level and a remediation range (area, depth, etc.) up to 1 m in depth [15].

In response to stakeholder requirements during a review process, the plant decided the site release criteria as 0.1 $mSv \cdot yr^{-1}$ including 0.04 $mSv \cdot yr^{-1}$ from groundwater. Exposure effect of subsurface soil was analyzed based on the resident farmer scenario in order to develop the surface soil DCGL and the subsurface soil DCGL separately. It was reasonably assumed that the resident farmer would be affected by contaminated subsurface soil due to future activities. The Microshield code was used for a calculation of the direct exposure dose and the RESRAD code for the groundwater contamination effect. The results showed that the subsurface soil DCGL was lower than the surface soil DCGL. Therefore, the surface soil DCGL value was also applied conservatively to subsurface soil [15].

3.5 Rancho Seco Nuclear Generation Station (RSNGS)

The plant divided the site into 8 areas and classified three contaminated areas (No. 1, 2, 8) based on historical spills or leaks during operation. The HSA identified the Regenerate Hold Up Tank (RHUT), CST, Auxiliary Building (AB) and TB drains and sumps as major contaminated areas. Further survey results showed that the Spent Fuel Pool (SFP) cooler pad area was confirmed as a Class 1 and then a contaminated soil was excavated up to 2.5 m in depth [23].

The plant applied an industrial worker scenario in the RESRAD modeling because facilities outside of the NPP such as the photovoltaic power station (3.2 MWe), the natural gas combined power plant (500 MWe) and the 220/230 kV substation will be continued to operate after a completion of the D&D project and a public access will be restricted to the remediated area.

The plant performed a comparative analysis with respect to the development of the site-specific DCGL for

Table 2. Summary of Subsurface Soil Remediation Case

NPP	Area	Date	Maximum Concentration of Radionuclides ($Bq\cdot g^{-1}$)	Remediation	Remarks
BRP	TB and CB base soil	1984~2005	^{137}Cs (1.957×10^{-1}) ^{60}Co (6.29×10^{-3}) ^{3}H (1,184 $Bq\cdot L^{-1}$)	Total 1,776 m^2 area excavated in 4 m	• ^{3}H in groundwater remediated as result of substructure excavation in 10.7 m depth and water removal. • ^{3}H concentration reached below the EPA drinking water limit in May 2004.
HNP	PAB and Storage tank area	1997~2007	^{60}Co (7.49) ^{137}Cs (3.59) ^{3}H (5,131 $Bq\cdot L^{-1}$)	About 11,700 m^2 area excavated in Max. 12.2 m	• Contaminated soil and groundwater remediation before long-term monitoring • Residual radioactivity confirmed below criteria in FSS
Dresden Unit 1	CST buried pipe (unit 2, 3)	2004~2009	^{3}H (118,400 $Bq\cdot L^{-1}$)	61 m of corroded pipes replaced and adjacent soil excavated in 3 m	• Groundwater assessment for total 0.33 ~0.37 million $Bq\cdot L^{-1}$ and result showed no remediation required (only monitoring) • Tritium plume located away enough from the residential area and below the limit
MY	RRA	1988~2005	^{137}Cs (7.4×10^{-2})	3 storage tank area excavated in Max. 1 m (Bedrock from 30 cm)	• Comprehensive remediation performed over the RRA • ^{3}H concentration significantly below the EPA drinking water limit in May 2002
RSNGS	SFP cooler pad	2002~2004	^{137}Cs (34.817) ^{60}Co (2.37×10^{-1})	Buried pipe removal with soil excavation in 2.5 m	• Soil remediation performed to the several storage tank area • No plant-generated radionuclides observed in the groundwater beneath the site

surface and subsurface soil. The results showed that the exposure dose was slightly increased to 0.38% in 1 m depth. However, applying a surface soil DCGL to subsurface soil was conservative because contaminants were assumed to be distributed over an entire area homogeneously.

Contrary to the previous assumption, subsurface soil contamination is usually confined to the discrete pockets rather than an entire area based on actual experiences on a site. Therefore, another analysis was performed incorporating the actual situations and the results showed that a maximum exposure dose from surface soil decreased with the depth of a discontinuous contaminated zone due to shielding effect. Therefore, the licensee decided to apply the surface soil DCGL value to subsurface soil for FSS [23].

4. Remediation Process Review

4.1 Subsurface Soil Remediation Technology

The characteristic survey results showed that the major contamination areas were storage tank areas and buried pipeline routes in the RCA. Immediate remediation was performed in the contaminated soil at the time of occurrence during the operation. However, repetitive leakages in these areas led to increase in residual radioactivity levels and a high concentration of contaminants in the surface soil migrated into the subsurface soil and groundwater. In this case, the plant decided to implement long-term monitoring

Table 3. Summary of Remediation Technology

NPP	Contaminated Media	Depth	Applied Technology
BRP	Substructure and Groundwater (CB)	10.7 m	• Engineering Confinement Structure - Slurry wall (side collapse/groundwater penetration) • Pump and Discharge System - Pump (stagnant water) - Vacuum extraction (free water inside the sub-floor vault) for ^{3}H in groundwater - Storage basin (water treatment before discharge)
HNP	Bedrock (PAB)	12.2 m	• Pump and Discharge System • Special equipment - Hydraulic Hammer (Hoe-Ram) - Explosive - High flow rate vacuum truck
Dresden Unit 1	Subsurface soil and Groundwater (CST)	3 m	• Pump and Treat - Storm drain system install - Pump into storage containers - Process the collected water by site waste processing system • Monitored Natural Attenuation - Contamination source eliminated (Excavated) - No indications of tritium moving towards resident area - Continue monitoring/sampling program
MY	Subsurface soil (RRA)	1 m	• Soil and Bedrock Removal (Excavation) - Two equipment operators and two laborers (Applied reduction rate : 95%) - Back and track hoe excavators with squared edge excavator bucket (minimize mixing of contaminated soil)
RSNGS	SF building	2.5 m	

of groundwater with or without remediation based on impact analysis results and the remediation strategy.

Major radionuclides identified in subsurface soil and groundwater were ^{60}Co, ^{137}Cs and ^{3}H. These are referred to as easy-to-detect radionuclides. In domestic experience of KRR-1 and 2, ^{60}Co and ^{137}Cs were identified as main contaminants [13]. ^{3}H was the only radionuclide in groundwater at most NPP sites with a significant potential of off-site migration, but its concentration level would decrease significantly over time.

In general, aggressive remediation technologies were applied to soil such as subsurface soil/bedrock excavation, and groundwater pumping, while passive remediation technologies were applied to groundwater (monitoring and natural attenuation) based on hydrogeological conditions and radionuclide concentrations at each NPP site [24]. (See Table 3)

Soil or fractured bedrock excavation is commonly used in soil remediation works as it is a very simple and effective method in a surface and subsurface soil both. For this reason, an extensive excavation was performed in wide areas at every NPP site in the U.S in order to reduce a residual radioactivity level by removal of contaminants in soil. In addition, a liquid radioactive waste system was added at three sites (BRP, HNP, and Dresden) for a treatment of extracted water before discharge because an excavation area needed to be dewatered. For example, a discharge system with continuous pumping to extract the contaminated water (flow rate : 0.03 $m^{3}\cdot s^{-1}$) was applied during the HNP D&D project. The Dresden site also performed dewatering before deciding long-term monitoring of contaminated groundwater [24].

A huge amount of excavated soil was produced as a result of remediation works at every NPP site which must be disposed of as radioactive waste. NRC allowed on-site disposal of slightly contaminated soil upon a request from the plant on a case by case. NRC required to follow the procedures and to provide the technical justifications, including an environmental impact assessment whether the backfilled excavated soil would be complied with the site release criteria.

4.2 Site Release Criteria Setting

Four federal laws in addition to the regulations of a state, tribal and local governments have historically regulated the remediation work of contaminated soil with radioactive material in the U.S. as follows :

- The Atomic Energy Act (AEA) of 1954
- The Uranium Mill Tailing Radiation Control Act (UMTRCA) of 1978
- The Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1984
- The Resource Conservation and Recovery Act (RCRA) of 1997

The authorized regulatory agencies such as EPA, NRC, and States are required to establish and regulate the standards by these laws. NRC was granted an original authority by AEA, later changed to the Department of Energy (DOE) by the Energy Reorganization Act (ERA) of 1974. From this Act, NRC changed its authority to regulate the remediation activities for commercial NPPs. EPA was granted an authority by CERCLA. Under this Act, EPA established a cleanup level for contaminated sites and a drinking water criterion as referred as MCL (Maximum Contaminant Level) in 40 CFR 141.16. The state EPA also reserved a right to request corrective actions to the contaminated sites that did not meet the regulatory criteria under RCRA [25].

Table 4. Summary of Site Release Criteria Evaluation

NPP	Release Criteria		Exposure Pathway	Specific Consideration
	Scenario	Limit ($mSv\cdot yr^{-1}$)		
BRP	Modified resident farmer (Greenfield)	0.25	• Site located in Lake Michigan shoreline is highly unlike to use subsistence farming so ingestion of animal products (meat and milk) are excluded	• Annual dose effect from tritium in the aquifer that could be used as drinking water supply in the future is considered
HDN	Resident farmer (Greenfield)	0.15	RESRAD standard pathway	• 0.25 $mSv\cdot yr^{-1}$ for site release criteria from US NRC and 0.19 $mSv\cdot yr^{-1}$ for property transfer from the State of Connecticut was considered • 0.15 $mSv\cdot yr^{-1}$ applied considering the effect of ^3H in groundwater (total 0.04 $mSv\cdot yr^{-1}$)
Dresden Unit 1	Deferred dismantling (SAFSTOR)			
MY	Resident farmer (Greenfield)	0.1	• RESRAD standard pathway with conservative • High-quality water facilities are available in the near residential area • Farmers are not likely to live at the site	• Enhanced state clean-up standard applied that 0.1 $mSv\cdot yr^{-1}$ for all pathways, including not more than 0.04 $mSv\cdot yr^{-1}$ from groundwater source of drinking water.
RSNGS	Modified Industrial worker (Brownfield)	0.25	• Ingestion (plant, meat) and aquatic food are excluded • Drinking water pathway included (current portable water wall exist)	• Occupancy would be limited to 50 workweek/yr (2,000 hours/yr) • Spent time while onsite (indoor/outdoor, 50/50)

It was found that stakeholders attempt to involve a decision-making process from the early phase of D&D projects and the plant shall consider their requirements as one of the key factors. Therefore, the plant developed LTP reflecting different criteria and needs from various stakeholders. NRC regulates the overall D&D process and provides standard guidelines while the stakeholders require a clear verification to the plant in terms of health and safety for the general public and the environment around the site. (See Table 4)

Each NPP site had different release criteria as a result of various exposure pathway analysis reflecting specific site conditions such as location, surrounding environment, residual facilities, contamination conditions, and local legislation.

The result showed that each site modified the scenarios and applied the different maximum dose criteria (0.1~0.25 $mSv \cdot yr^{-1}$) to fulfill their intended purpose (greenfield or brownfield) with a conservative approach. The different state's requirements must also be met in order to use the released site under local regulations. For this reason, HDN and MY applied the lower release criteria to reflect the requirements of each state.

In addition, the effects on groundwater were conservatively considered and the NPP sites such as BRP, HNP, MY and RSNGS assigned a certain portion of dose value to the groundwater-oriented exposure effect. Most NPP sites had tritium contamination. However, the environmental assessment of each site showed that residual radioactivity was not high enough to require a comprehensive remediation work.

5. Conclusion

Kori unit 1 completed HSA based on the MARSSIM process in 2018 [26] and began planning the characterization survey [27]. The remediation experience of a subsurface soil was comprehensively reviewed for five NPP sites in the U.S. and summarized in each category such as a planning, technical background, standards and regulatory guidelines and strategy to provide the background information for preparedness of the Kori unit 1 D&D project.

The current MARSSIM procedure does not provide formal guidance to a subsurface soil, unlike a surface soil due to inherent characteristics. Each plant performed a case-by-case evaluation by analyzing an exposure impact of a subsurface soil contamination to establish a technical background. According to the results of the analysis, it was confirmed that the effect of radiation exposure was limited by soil depth and the radioactive level of subsurface soil does not exceed the surface soil. Therefore, the plant conservatively applied the surface soil DCGL value to the subsurface soil and performed comprehensive soil remediation work.

In addition, most of the sites considered the possibility of groundwater contamination when any subsurface soil contaminations were found. It was decided to perform long-term monitoring of groundwater without remediation at the Dresden unit 1 site with the site restoration to be performed together with units 2 and 3 later. The long-term monitoring remediation strategy can be considered in the D&D project of the Kori site (units 1 to 4).

The US NRC recognized the limitations of assessment, review and performance evaluation of subsurface soils due to the high uncertainty in NUREG/CR-7021 [12]. Even though the current system has some limitations for subsurface soil, NRC emphasized the importance of establishing specific technical standards and guidelines based on the accurate evaluation of subsurface soil contamination to adequately assess the risk [28]. DCGL should be derived considering the depth of contamination to avoid significant overestimation or underestimation of the actual site condition. Overestimation will result in an increase of remediation costs and the volume of radioactive waste as well as delay in the D&D schedule. Underestimation will increase potential risk to the public and environment and possibly interrupt or delay site release process as a result of FSS.

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