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CONTAMINATION CONTROL, RADIOLOGICAL SURVEY, AND DOSE MODELING CONSIDERATIONS TO SUPPORT LICENSE TERMINATION AT SITES WITH ENVIRONMENTAL DISCRETE RADIOACTIVE PARTICLE CONTAMINATION

DRAFT FOR COMMENT

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EXECUTIVE SUMMARY

The U.S. Nuclear Regulatory Commission (NRC) has developed this interim staff guidance (ISG) for evaluating the adequacy of licensees' plans for contamination control, survey strategies, and dose modeling for sites with known or potential discrete radioactive particle (DRP) contamination found in the onsite environment at any phase of decommissioning because of an uncontrolled release. Licensees should make reasonable efforts to ensure that risk-significant DRPs are not present when demonstrating compliance with unrestricted release criteria. Risk-significant DRPs are those that would cause public dose limits and license termination dose constraints to be exceeded. DRP contamination control, surveying, and dose modeling methods should be emphasized early in the decommissioning process to ensure the adequacy of remediation planning and final status survey (FSS) planning, and ultimately risk-inform license termination assessments.

Identification and corrective actions addressing DRPs can occur during operational monitoring, site characterization, or remedial action support surveys, all of which should occur before the FSS. When DRPs are identified at the time of FSS, it is highly likely that additional resources will be expended to address DRP contamination, and license termination may be delayed. Further, since DRPs can be generated during certain decommissioning activities, as explained in this ISG, it is prudent for licensees to understand the potential impacts to the decommissioning process and examine the adequacy of their programs for radiation protection, contamination control, and surveys and monitoring, as well as the associated implementing procedures.

This ISG identifies guidance specific to DRP survey planning such as the application of select aspects of the Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM, NUREG-1575) to surveys for DRPs, establishment of data quality objectives for surveying for DRP contamination, and proof of concept protocols if new technologies are to be used. This ISG also provides general guidance on DRP surveys for the outdoor environment. Further, this ISG provides guidance on timely communication with the NRC and DRP documentation strategies to be taken when identifying DRPs in the environment at a site.

In addition, this ISG provides guidance for developing and evaluating dose compliance scenarios for sites with a history of DRP contamination and remediation during decommissioning. DRPs identified during the decommissioning planning or implementation phases should be collected, documented, and dispositioned appropriately. To risk-inform the decision to terminate the license, the probability of unidentified DRPs remaining at the time of license termination and the potential for public exposure should be considered. The guidance addresses approaches to develop reasonably foreseeable future land use exposure scenarios and the use of the less likely but plausible scenarios for a very low likelihood of public exposure to DRPs after license termination. These scenarios can contribute to risk-informing decisions on unrestricted use as part of the overall compliance demonstration.

The ISG process allows staff to identify and address specific areas in guidance documents that need to be revised, until the appropriate NRC regulatory guidance can be updated. This ISG is expected to increase consistency in future licensee submittals and staff reviews and represents the NRC's commitment to addressing stakeholder needs including consideration of modern approaches to demonstrating compliance with the radiological criteria for license termination. The NRC is issuing this document for public comment. Comments received on the draft document will be addressed in a comment response document, and a final guidance document

will be issued. The final ISG document will be incorporated into future established guidance revisions.

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ABBREVIATIONS AND ACRONYMS

Ac	Actinium
ADAMS	Agencywide Documents Access and Management System
ALARA	as low as reasonably achievable
Am	Americium
Ar	Argon
Ba	barium
Bq	Becquerel
Ca	Calcium
CEDE	committed effective dose equivalent
CFR	*Code of Federal Regulations*
Ci	Curie
cm	Centimeter
Cm	Curium
Co	Cobalt
Cs	Cesium
d	Day
DandD	Decontamination and Decommissioning (computer code)
DC	dose coefficient
DE	dose equivalent
DP	decommissioning plan
DQO	data quality objective
DRP	discrete radioactive particle
EDE	effective dose equivalent
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
Eu	Europium
Fe	Iron
FGR	Federal Guidance Report
FSS	final status survey
FSSP	final status survey plan
g	Gram
GI	gastrointestinal tract
h	hour
HSA	historical site assessment
ICRP	International Commission on Radiological Protection
IMBA	Integrated Modules for Bioassay Analysis
IN	information notice
ISG	interim staff guidance
kBq	kilobecquerel
LDE	localized dose equivalent
LLBP	less likely but plausible
LTP	license termination plan
MARSSIM	Multi-Agency Radiation Survey and Site Investigation Manual
MCNP6®	Monte Carlo N-Particle Version 6®
MDA	minimum detectable activity
mg	milligram
MQO	measurement quality objective
μCi	microcurie

μm	micrometer
m/s	meters per second
mrem	millirem
NCRP	National Council on Radiation Protection and Measurements
Ni	nickel
NRC	U.S. Nuclear Regulatory Commission
NUREG	NRC technical report designation
NUREG/CR	contractor-prepared NUREG
ORISE	Oak Ridge Institute for Science and Education
PiMAL	Phantom with Moving Arms and Legs
PNNL	Pacific Northwest National Laboratory
Pu	plutonium
Ra	radium
RESRAD	RESidual RADioactivity (computer code)
RV	reactor vessel
SDE	shallow dose equivalent
Sr	strontium
Sv	sievert
TEDE	total effective dose equivalent
Th	thorium
URT	upper respiratory tract

1. Introduction and Purpose

The U.S. Nuclear Regulatory Commission (NRC) regulations on license termination criteria (Title 10 of the *Code of Federal Regulations* (10 CFR) Part 20, "Standards for Protection Against Radiation," Subpart E, "Radiological Criteria for License Termination") are performance based, allowing the licensee flexibility in demonstrating that the residual radioactivity at its site meets the license termination requirements. This regulation applies during operations and through license termination. In addition, NRC regulations on radiation protection programs (10 CFR Part 20, Subpart B) and surveying and monitoring for radioactivity (10 CFR Part 20, Subpart F) apply to licensed facilities through license termination. Subpart B and Subpart F are integral to demonstrating compliance with Subpart E.

To support licensees and the staff, the NRC has developed a series of NUREGs for use by licensees to develop, and the staff to evaluate, the decommissioning plans (DPs), license termination plans (LTPs), and final license termination requests. The core document providing guidance regarding surveys to identify and support the amount of residual radioactivity present at a site and the dose consequences of that residual radioactivity is NUREG-1757, Volume 2, Revision 2, "Consolidated Decommissioning Guidance: Characterization, Survey, and Determination of Radiological Criteria," issued July 2022 (NRC 2022a). The consolidated guidance includes review criteria (e.g., in Chapters 4, "Facility Radiation Surveys," and 5, "Dose Modeling Evaluations") and appendices with potential approaches to the range of site-specific issues that may arise, generally using graded approaches. Federal guidance for radiological surveys during all phases of the radiological survey and site investigation process can be found in NUREG-1575, Revision 1, "Multi-Agency Radiation Survey and Site Investigation Manual" (MARSSIM), issued August 2000 (NRC 2000). More detailed guidance on instrument sensitivity for radiological surveys appears in NUREG-1507, "Minimum Detectable Concentrations with Typical Radiation Survey for Instruments for Various Contaminants and Field Conditions."

One form of non-diffuse contamination, discrete radioactive particles (DRPs),[1] has resulted in challenges during active decommissioning at some NRC-licensed power plants. The issues related to DRPs observed during decommissioning have involved DRP containment and contamination control, performance of adequate surveys for DRPs, and approaches to demonstrating compliance with 10 CFR Part 20, Subpart E, when considering past DRP environmental contamination.

The current decommissioning guidance described above focuses on addressing diffuse residual radioactivity with respect to performing surveys and assessing potential public exposure after license termination. The current guidance does not address and is not appropriate as guidance for DRP contamination. For example, MARSSIM guidance focuses on radiological survey approaches for diffuse residual radioactivity found in surficial materials (e.g., typically the top 15 centimeters (cm) of soil) and does not apply to DRPs that may be present in the environment

[1] DRPs, or hot particles, have historically been considered small, high-activity particles less than 1 millimeter in any dimension that are insoluble in water. These have historically been small pieces of activated metal from reactor internal fixtures released due to wear or spent fuel particles released from fuel rod failures. However, from a decommissioning perspective, particles could also include larger pieces of activated metal or concrete generated by segmentation efforts. The primary consideration is that DRPs are relatively small, high-activity particles or objects (e.g., large concrete chips) that approximate a photon-emitting point source when surveying in open land areas, are generally insoluble in water, and have characteristics and potential exposure scenarios that are inconsistent with diffuse residual radioactivity in soil or on structural surfaces.

and would typically have exposure scenarios different from those associated with diffuse contamination in soil or on structures. DRP exposure scenarios could include inhalation or ingestion of small DRPs. DRPs could come in contact with an individual's skin or clothing, or larger DRPs could be pocketed or collected and result in a longer period of exposure. Because the current radiological environmental survey and dose assessment guidance to support license termination does not address DRP contamination, the NRC staff has approached each past instance of this contamination on a case-by-case basis.

While guidance on control of radioactively contaminated material exists, there is no guidance on the control of DRP contamination in the environment other than NRC Information Notice (IN) 2024-01, "Minimization and Control of Contamination Involving Discrete Radioactive Particles at Decommissioning Facilities," dated February 9, 2024 (NRC 2024). That NRC Information Notice, IN 2024-01, informed licensees of recent challenges involving detection and contamination control of DRPs, including providing several recent examples of lessons learned from recent DRP issues. This interim staff guidance (ISG) is intended to provide more detail regarding control of DRP contamination in the environment with special emphasis on the use of the MARSSIM data life cycle concept to plan surveys and removal of DRP contamination to assist in site decommissioning. This ISG also discusses DRP contamination in key decommissioning planning documents such as historical site assessments (HSAs), post shutdown decommissioning activities reports, and LTP license amendment requests. If contamination control programs and survey and monitoring programs at decommissioning facilities that have the potential to generate DRPs as a result of certain decommissioning activities are not designed with DRPs in mind, it is highly possible that licensees may not be able to adequately survey and monitor for them because DRP detection sensitivities, survey rates, and instrumentation requirements often differ from those used for the diffuse contamination normally considered in decommissioning.

This ISG contains no substantive changes to the review criteria for diffuse contamination in the main chapters of NUREG-1757; NUREG-1700, Revision 2, "Standard Review Plan for Evaluating Nuclear Power Reactor License Termination Plans," issued April 2018 (NRC 2018); and NUREG-1575. This ISG provides new review criteria for DRPs in the form of guidance for licensees to consider when a licensee either has DRPs as a site characteristic (i.e., DRP contamination exists due to a previous unplanned release) or chooses to conditionally address DRPs in its LTP or DP (e.g., to address the possibility of DRPs being created during decommissioning).

2. Discrete Radioactive Particles

2.1. Discrete Radioactive Particles and Their Source

DRPs are small, relatively high-activity particles that are generally considered insoluble in water. They can range in size from microscopic up to several centimeters in diameter. The smaller the particle, the greater the possibility of it being charged and electrostatically attracted to other materials, which may create difficulties in contamination control. Smaller particles also increase the possibility of an uptake (e.g., inhalation or ingestion) as a route of exposure, although the radioactivity associated with a particle is generally expected to decrease significantly as the total amount of material (i.e., the size of a DRP) decreases. Also, DRPs are not readily assimilated into the environment and therefore cannot typically be evaluated using common environmental pathway analysis decommissioning software such as RESRAD (RESidual RADioactivity (computer code)) or DandD (Decontamination and Decommissioning (computer code)).

Examples of DRPs found at NRC-licensed facilities during decommissioning include neutron-activated metals (e.g., legacy particles from equipment wearing, cuttings from segmentation of reactor vessel (RV), RV internals, rebar in bioshield), spent fuel fleas from damaged fuel, and neutron-activated concrete chips from the bioshield. Less common examples of DRPs could include natural thorium (Th) in pieces of slag from thoriated welding rods and lost or damaged sources (e.g., Am-241 foils from damaged smoke detectors).

The following provides a brief overview of the origin and characteristics of each type of DRP and describes the NRC's reactor decommissioning regulatory framework for DRPs. Much of the information summarized below is derived from comprehensive reviews by Charles and Harrison (2005), the Electric Power Research Institute (EPRI 1988, 1994), Lang et al. (1995), Dionne and Baum (1991), the National Council on Radiation Protection and Measurements (NCRP 1999), and the NRC (2001).

At nuclear power plants, DRPs may be created both during normal operations and decommissioning activities. Wear-resistant alloys used in components like valve seats and reactor coolant pumps are a common source of DRPs at operating nuclear power plants. These alloys include Stellite™, which is a cobalt-chromium alloy, and Inconel™, an austenitic nickel-chromium alloy. As these components wear, small fragments containing the stable cobalt (Co) isotope Co-59 are neutron-activated to Co-60, a beta-gamma-emitting radionuclide with a 5.27-year half-life (NCRP 1999). The distribution of activity of Co-60 DRPs is log-normal, with pressurized-water reactors tending to have larger activities per particle than boiling-water reactors (22 kilobecquerels (kBq) versus 5.9 kBq) (NCRP 1999). During decommissioning, a licensee may encounter these particles when dismantling the systems and components where particles generated during plant operation have settled.

Failed fuel is a common cause of irradiated fuel fragments at nuclear power plants. The distribution of activity in irradiated fuel fragments is log-normal with an arithmetic average activity of 15 kBq and geometric mean of 3 kBq (NCRP 1999). At decommissioning nuclear power plants, most irradiated fuel fragments will have undergone sufficient radioactive decay such that short-lived radionuclides are no longer detectable. The remaining long-lived dose-significant radionuclides in irradiated light-water reactor fuel fragments include strontium (Sr)-90, cesium (Cs)-137, plutonium (Pu)-238, Pu-239, Pu-240, and americium (Am)-241 (Hedin 1997).

Decommissioning activities themselves may also generate DRPs. During decommissioning activities, the use of mechanical cutting tools such as grinding wheels, plasma torches, band saws, reciprocating saws, and oxy-acetylene torches can create DRPs containing primarily Co-60 (DOE 1998, 2000; Ebadian et al. 2001; Newton et al.1987; Onodera et al. 1991).

For decommissioning operations, much of the RV internals will also be removed and sectioned. The cuttings can result in DRPs from the activated alloys such as Monel or other materials. In addition, rebar in bioshield concrete can become activated and may be a source of DRPs if contamination control practices are not adequate.

Fragments of activated bioshield are created at decommissioning nuclear power plants when the concrete is being prepared for disposal. In general, radionuclides in activated bioshield are the activated concrete constituents and include argon (Ar)-39, Co-60, iron (Fe)-55, calcium (Ca)-41, nickel (Ni)-63, barium (Ba)-133, europium (Eu)-152, and Eu-154 (see table 7.3-6 of NUREG/CR-0130, Volume 1, "Technology, Safety and Costs of Decommissioning a Reference Pressurized Water Reactor Power Station," issued June 1978 (NRC 1978)).

Demolition and decommissioning activities can generate or release DRPs that were unknown to be present in equipment or components being removed or dismantled as part of the decommissioning process. The inadvertent or unintentional DRP contamination of soil can occur during waste loading of DRP-contaminated waste or from a lack of sufficient ventilation and containment during waste handling operations of DRP-contaminated waste. Use of large construction equipment during the disassembly of structures and system components, as well as for loading waste and site preparations, poses challenges for contamination control during decommissioning. Inclement weather due to storms or tornados may create flooding that could result in the spread of DRP environmental contamination. In addition, high winds also may damage containment tents that may result in an unplanned release of DRPs.

2.2. Regulatory Requirements Applicable to Discrete Radioactive Particles

Occupational radiation protection requirements and guidance[2] applicable to DRPs was established several decades ago, but little or no guidance is available on public exposures because the assumption has been that such materials would either generally be controlled and not impact the public or else would be considered on a case-by-case basis. Regardless, DRPs are primarily a risk for deterministic effects and, as such, occupational limits protecting against deterministic effects should be similarly protective to a member of the public.

The NRC staff considers the following regulatory requirements to apply to residual DRPs during decommissioning and hypothetical public exposure after license termination:

- performance of appropriate surveys (10 CFR 20.1501, “General,” and 10 CFR 50.82(a)(9)(ii)(D))
- license termination requirement for unrestricted use (10 CFR 20.1402, “Radiological criteria for unrestricted use”)—25 millirem (mrem)/year total effective dose equivalent (TEDE)
- public dose limit (10 CFR 20.1301, “Dose limits for individual members of the public”)—100 mrem/year TEDE

Occupational dose limits (see 10 CFR 20.1201, “Occupational dose limits for adults.”) do not apply to the license termination compliance demonstration, although they could be used to risk-inform decisions about license termination. However, for facilities with a history of onsite DRP environmental contamination, the NRC staff will consider whether the licensee has adequately identified and removed risk significant DRPs (those that could potentially exceed the occupational deterministic effect limits in 20.1201 (limits of 50 rem/year shallow dose equivalent (SDE) for skin, and 50 rem/year committed dose equivalent (CDE) to organ) in the onsite environment based on the data quality objectives (DQOs) and measurement quality objectives

[2] IN 90-48, “Enforcement Policy for Hot Particle Exposures,” dated August 2, 1990 (NRC 1990); IN 87-39, “Control of Hot Particle Contamination at Nuclear Power Plants,” dated August 21, 1987 (NRC 1987); NUREG/IA-0535, “Using VARSKIN for Hot Particles Ingestion Dosimetry Evaluation,” issued September 2022 (NRC 2022a); Regulatory Guide 8.34, Revision 1, “Monitoring Criteria and Methods to Calculate Occupational Radiation Doses,” issued August 2022 (NRC 2022b); and IN 2024-01.

(MQOs) for the final status survey plan (FSSP) when evaluating the licensee's final status survey (FSS) compliance submittals and final dose compliance demonstration.

The NRC staff notes that the SDE (or localized dose equivalent (LDE)) is not a contributor to TEDE, so it is not directly applicable to the decommissioning unrestricted use dose limit. However, if DRP contamination is known or suspected, even if identified through a survey and verified by remedial survey to have been removed from the onsite environment, evaluation of the potential SDE and LDE to internal organs is useful to risk-inform decisions on license termination. Also, while the typical area assessed for averaging SDE is 10 cm^2, it may be more appropriate to consider 1 cm^2 for a member of the public, particularly if assessing potential LDE to an internal organ.

3. Contamination Control

3.1. Background

DRP movement in the environment, as well as in the workplace, can be unpredictable and thus worker contamination and environmental contamination are difficult to control. DRP contamination guidance was addressed in the early 1990s (NRC, 1990). The guidance focused on occupational contamination control as the primary means of controlling DRPs as opposed to exposure control, for various reasons as explained in SECY-98-45, "Rulemaking Plan for Protection Against Discrete Radioactive Particle (DRP) Exposures—10 CFR Part 20," dated October 23, 1998 (NRC 1998).

Licensees have found DRPs in the workplace during operations and have addressed the DRP contamination through their radiation protection programs and procedures and contamination control programs and procedures. For example, when DRPs have occurred in the work environment, the licensees have increased the frequency of monitoring personnel working in areas with potential for DRP contamination, as well as the frequency of area monitoring for areas suspected of being potential sources of DRPs. Licensees should be aware that during decommissioning, it is important to continue contamination control practices for DRPs. Good practices should focus on avoiding the spread of DRP contamination, containing the DRP contamination, removing DRPs from the decommissioning environment, and maintaining exposure as low as reasonably achievable (ALARA). DRP exposure control should incorporate the design of a workplan survey and decontamination program for both areas and personnel that provides reasonable assurance that most personnel will not be exposed to DRPs and that DRP environmental contamination will be avoided, and that those who are unavoidably exposed to DRPs will receive doses that are within an acceptable level.

DRPs generated through decommissioning activities should be controlled at the source, but if a release to the environment occurs, licensees should take corrective action to identify the extent of release, remediate as appropriate, and document survey results. This should be done expeditiously to avoid secondary environmental transport.

Existing regulatory requirements and guidance specific to contamination control are summarized below. However, they do not mention residual DRPs. As stated earlier, radiation protection requirements for DRPs can apply to both occupational personnel and the public. DRPs can contribute a significant dose and therefore should be cleaned up as soon as possible to avoid cross -contamination.

In 1997, the NRC improved decommissioning planning by establishing a new regulation at 10 CFR 20.1406, “Minimization of contamination,” and amending the regulation in 10 CFR 20.1501(a) (76 FR 35511). These regulations state that surveys of areas to evaluate residual radioactivity include the subsurface. As described in the 1997 final rule, “residual radioactivity” that is significant for decommissioning planning is a quantity of radioactive material that would require remediation to meet the unrestricted use criteria of 10 CFR 20.1402. In 2024, the NRC issued IN 2024-01 to inform licensees of recent challenges involving detection and contamination control of DRPs, commonly referred to as hot particles, during plant operations and decommissioning. That communication was intended to reinforce compliance with the 10 CFR 20.1501 requirement to use appropriate survey practices to detect and, in coordination with 10 CFR 20.1406, to reduce the spread of residual radioactivity.

In June 2008, the NRC issued Regulatory Guide 4.21, “Minimization of Contamination and Radioactive Waste Generation: Life Cycle Planning” (NRC 2008), and, in December 2012, Regulatory Guide 4.22, “Decommissioning Planning during Operations” (NRC 2012). Both regulatory guides are focused on contamination control during design and operations to facilitate future decommissioning. This ISG focuses on contaminant management and control during active decommissioning, with a threefold approach: (1) prevention of unintended releases, (2) early detection if there is an unintended release of radioactive contamination, and (3) prompt assessment to support a timely and appropriate response.

Consistent with 10 CFR 50.75(g) requirements for reactor licenses, reactor licensees maintain records of spills or other unusual occurrences involving the spread of contamination in and around the facility, equipment, or site until the license is terminated. The regulation applies to events that occur while the plant is operating and during decommissioning. The requirement outlined in 10 CFR 20.1501(b) is associated with the existing 10 CFR 50.75(g) provisions in requiring that survey records of subsurface residual radioactivity are kept with records important for decommissioning.

The records required by 10 CFR 50.75(g) may be limited to instances when significant contamination remains even after cleanup procedures are used or when there is a reasonable likelihood that contaminants may have spread to inaccessible areas or porous materials. The records continue to be required through license termination. The 50.75(g) records should be used to inform decommissioning planning and the data life cycle. DRP contamination inside buildings, as well as in the environment, should be cleaned up as soon as possible and documented. For reactors, a best practice would be to document the DRP contamination cleanup in 10 CFR 50.75(g) records to inform decommissioning planning.

Additionally, consistent with NUREG-1757, Volume 2, Revision 2, and NUREG-1575, Revision 1 (MARSSIM), when preparing for decommissioning, licensees should conduct an HSA, which, in part, identifies all previous site releases, to include any DRP releases, and areas where supplemental characterization is needed to adequately plan and prepare for decommissioning the site. The site characterization is then performed to gather the information needed to fully identify areas needing remediation and make plans for decommissioning and demonstrating compliance with 10 CFR Part 20, Subpart E, for license termination. During decommissioning operations, additional surveys are normally performed to assess any remediation being performed to ensure that the remediation has achieved its purpose. It is only after all these steps that an FSS is performed to demonstrate compliance with the license termination criteria.

3.2. Contamination Control Practices for Discrete Radioactive Particles

Licensees are responsible for ensuring that there are adequate controls and monitoring to minimize the probability and impact of a release of radioactivity into the environment. During operations, licensees have a robust, established contamination control program. During the transition from operations to decommissioning, licensees should continue, and possibly expand, the contamination control program for decommissioning, especially if DRP contamination has occurred during operations or may occur on site during decommissioning activities.

3.2.1. Adequate Controls During Risk-Significant Decommissioning Activities

During decommissioning, adequate controls should be incorporated into risk -significant equipment and structural removal activities. The nature of such activities often involves challenges to contamination control, such as cutting openings in containment to remove large waste containers, which may reduce the effectiveness of area isolation and use of air flow to contain contamination. While decontamination efforts are normally performed at the waste loading location, licensees should consider establishing supplemental staging areas immediately outside of areas of high background radiation where containers could be surveyed for contamination before being moved to potentially nonimpacted parts of the site. Similarly, any large equipment used in areas of known DRP contamination should be surveyed and decontaminated, as appropriate, before being relocated.

As deconstruction of the primary containment and support buildings occurs, routine surveys of heavy equipment should be part of the contamination control program to ensure that equipment does not transport contamination. Similarly, routine surveys of waste preparation/loading, haul paths, and storage or staging areas should be incorporated into the contamination control program. Efforts should be made to properly isolate remediated areas and the locations where any further surveys of equipment will be conducted once an area is turned over to the FSS stage. Also, routine surveillance of isolated survey units should occur to ensure that ongoing operations have not impacted the areas released for FSS.

Should DRP contamination be discovered in an area that has been turned over for FSS, the status of the area may need to be downgraded while DRP surveys and remediation are performed. If the FSS has already been performed, the scanning and surveys of the potentially affected survey units should be reviewed to confirm that the survey was performed with adequate sensitivity and diligence to meet data quality objectives suitable for risk significant DRP identification. After DRP remediation and a survey to confirm DRP removal, the FSS should be re-performed for the survey units involved. Licensees should note that the NRC is likely to consider such situations for confirmatory surveys. After a FSS survey unit has been found acceptable to the licensee, it should be isolated to minimize the possibility of being contaminated through ongoing activities. Disturbance of such units would require resurvey. Also, no passive use, such as the storage of clean material and or equipment, should occur.

The NRC staff considers that the presence of DRPs at the time of FSSs during the license termination process is an indication that a licensee's contamination control program may be inadequate and may not comply with 10 CFR 20.1406. While the staff recognizes that human error and difficulties in surveying for DRPs may result in their sporadic identification at the time of FSSs, multiple occurrences of DRPs being identified during FSSs could call into question the licensee's performance during previous surveys and/or implementation of corrective actions.

3.2.2. Adequate Surveys of Discrete Radioactive Particles During Operation and Decommissioning

Disassembly of structures and systems using large equipment, as well as inclement weather, could result in a release and spread of contaminated material. For this reason, monitoring and routine surveying of areas that may be affected are necessary to protect public health and safety and the environment. Survey plans may need to be frequently adjusted to incorporate ongoing deconstruction operations, temporary waste loading areas, waste haul paths, and waste packaging areas that present a risk of spreading contamination across a site.

Surveys specifically designed to identify DRPs should be considered as a routine practice that continues through license termination, especially when known, suspected, or unplanned DRP releases to the environment have occurred. A summary of DRP surveys conducted during plant operation should be documented in either the HSA or 10 CFR 50.75(g) file, as appropriate.

The initial identification of a DRP release often occurs during personnel frisking as workers leave an area where DRPs may have been released. So long as the release occurs within a controlled environment, it may not rise to the level of regulatory concern if the conditions and exposure levels are well documented and meet regulatory limits. This ISG becomes applicable only when an uncontrolled release to the environment occurs. If an unplanned release of DRP contamination or potential release of DRP contamination might occur during decommissioning, the licensee should re-examine (1) its data life cycle protocols to ensure that its DQOs and MQOs remain appropriate and (2) whether an amendment to the LTP or DP is needed. Communication with the NRC staff as early as possible is important when such a release has or potentially may occur.

DRP contamination surveys should be performed expeditiously after any identified release to the environment. Corrective actions should be taken to both collect the DRPs and minimize the potential for secondary transport mechanisms to spread or cover the contamination before remediation. The results of the DRP survey(s) and the impacted site area, as well as any remediation or alternate decision-making, should be documented in the licensee's corrective action system, 10 CFR 50.75(g) file, or both. It may also be prudent to assess a statistically significant number of particles to identify which radionuclides of concern may be present and the estimated range of DRP radioactivity and size involved in the release. This detailed documentation of the event and the licensee's response will minimize uncertainties about the final site conditions at license termination.

3.3. Applicability of ALARA for Discrete Radioactive Particles

The ALARA concept pertains to DRPs in that, when making reasonable efforts to identify DRPs resulting from licensed activities in the environment, it should be considered an ALARA practice to collect and disposition identified DRPs so that no known DRPs remain at the conclusion of remediation efforts. While this ISG will focus on evaluating the potential risk of DRPs to a member of the public and identifying DRPs of potential dose significance when designing surveys, any DRP resulting from licensed activities that is identified in the environment should be collected and dispositioned appropriately.

3.4. Considerations for Discrete Radioactive Particle Surveys

In developing the plan for the range of surveys during decommissioning activities including the final status survey plan, the licensee should utilize a risk-informed, performance-based

approach. The licensee should consider operational information including information collected in accordance with 10 CFR 50.75(g) and additional information obtained through the development of the HSA and site characterization activities which will establish a baseline of the state of the site and a range of residual radioactivity present, including possible DRPs. Using this information, decommissioning activities such as dismantlement plans, decommissioning methods, and waste management strategies can be informed on places where DRPs may be encountered, created or accidentally dispersed if mitigation methods fail. For example, DRPs could be generated during active decommissioning by reactor and bioshield segmentation activities or released when removing connected systems and equipment where hot particles may have settled during plant operations. If adequate controls are in place during operations to contain and appropriately disposition[3] DRP contamination, then it may be reasonably justified that no DRP contamination was released to the environment during operations. Similarly, if a known release occurred and an appropriate and timely effort was made to survey and remediate the release, then it may be reasonably justified that no DRPs remain in the area.

When a licensee develops or modifies its DQOs for the FSS of potentially affected survey units, licensees should consider the possibility that DRPs may exist because of human error during previous surveys or remediation process, or challenging field conditions existed during the survey. If a DRP contamination event (unplanned release of DRPs) to the environment has been identified or is suspected, then the survey guidance in section 4 of this document is relevant for establishing the survey methods used to support remediation of the event. If previously unknown DRPs are discovered during support surveys or FSSs, the licensee should consider whether a resurvey of an area is warranted using more conservative scanning methods to determine if DRP contamination is significant or widespread. f DRPs are found during the FSS, the FSS methods should be assessed to verify there was appropriate sensitivity and training for detecting DRPs during the survey. If the FSS sensitivity was not 10%-50% of the activity level of concern for DRPs (see section 4 of this guidance), then the FSS should be redesigned with appropriate DQOs and MQOs and re-performed.

3.4.1. The Data Life Cycle

One method to risk-inform and performance-base the survey plans is to use the MARSSIM (NUREG-1575) data life cycle. There are four phases of the data life cycle: the planning phase, the implementation phase, the assessment phase, and the decision-making phase. Survey planning uses the DQO Process, which is a series of logical steps to create a plan for the resource-effective acquisition of environmental data, to ensure that the survey results are of sufficient quality and quantity to support the final decision. Using the DQO Process ensures that the type, quantity, and quality of environmental data used in decision-making will be appropriate for the intended application. The DQO Process should address DRPs when the site has a history of DRPs in the environment or there is reason to believe that decommissioning activities will generate or spread DRP contamination such that a potential release to the environment is plausible.

Further, MQOs are an important subset of inputs into the DQO Process that define performance requirements and objectives for the measurement system. MQOs that should be considered

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[3] "Dispositioned appropriately" means demonstrated to be removed by sample collection or waste disposal and verified to be completely remediated using remedial survey methods planned with DQOs and MQOs specific to the site DRPs.

include method uncertainty, detection capability, range, specificity, and ruggedness. With respect to DRPs, it is necessary to understand what constitutes a risk significant DRP which is why scenario modeling and estimating the potential dose from exposure to a DRP are necessary. Once a DRP of significant risk is determined, the sensitivity and uncertainty of the measurement instrumentation and surveying methods in differing field conditions can be assessed. One way to minimize measurement uncertainty and increase sensitivity for DRPs is to ensure that DRP contamination is identified and DRPs are collected and dispositioned in a timely manner after the release occurs; this avoids situations in which DRPs may become covered or less easily detected by typical survey methods. Scanning surveys should be performed as slowly and with the detector as close to the surface as is practical, with significant diligence on the part of the surveyor to investigate perceived elevations in the count rate. More than one scanning survey may be performed in an area if human error may significantly decrease the reliability of the survey because of either training or field conditions.

4. Discrete Radioactive Particle Surveys and Dose Assessment

4.1. General Considerations

Consistent with 10 CFR 50.82, “Termination of license,” specific information is required in a license termination plan (LTP). Any history of DRPs in the environment should be included in the HSA or site characterization summary that serves as the basis for the LTP. However, the HSA and site characterization activities are often completed well in advance of when the LTP is submitted to the NRC, and may occur before many of the segmentation and dismantling activities that could contribute to the spread of contamination. In some cases, contamination events have occurred after the LTP license amendment request was submitted to the NRC and even after the LTP was approved. If DRPs are suspected to be present in the environment at the time of the FSS, the licensee should also communicate the occurrence to the NRC project manager. Depending upon the licensee’s strategy to address DRPs, the LTP or DP may need to be revised.

As described in NUREG-1700, the LTP should describe the techniques that will be used to remove or remediate surface and subsurface soils, ground water, and surface water and sediments. DRPs may become an issue even at sites with no history of fuel failure or releases during operation because DRPs may be produced and released during the segmentation or dismantling of RV internals and other contaminated piping, equipment, or components. If decommissioning operations have the potential to release DRPs into the environment, then the LTP or DP should discuss how the licensee plans to address potential DRP contamination. DRP contamination control management should be continued from operations to decommissioning.

In 10 CFR 50.82(a)(9)(ii)(D), the NRC requires an FSSP to be submitted (a FSSP is considered a “detailed plan for the final radiation survey” discussed in the regulation). FSSPs should describe how a licensee will demonstrate that residual radioactivity at the site meets the radiological criteria in 10 CFR Part 20, Subpart E. FSSs rely on a combination of statistically determined sampling to assess the average level of residual radioactivity and scanning to identify areas of significantly increased concentrations of residual radioactivity (elevated areas). Guidance for FSSPs can be found in NUREG-1757, Volume 2, and MARSSIM, which primarily focus on diffuse residual radioactivity that may be present on surfaces of structures and in surface soil. The FSS should incorporate appropriate scanning methods that will support the DQOs and MQOs for impacted survey units.

Early communication between the licensee and the NRC is essential during all four phases of the data life cycle. If DRPs need to be considered as a characteristic at the time of license termination, the LTP or DP should address how the licensee will survey for, identify, and evaluate the risk of DRPs to demonstrate compliance with the release criteria. Ideally, DRPs should be identified and remediated before the FSS begins.

FSSPs and remedial action support surveys should be developed using DQOs and MQOs appropriate for DRPs, if known or suspected to be present, as well as for diffuse area contamination similar to discussions in MARSSIM. The LTP or DP should address the MDA for DRPs for the instrumentation that will be used, and the licensee should consider the potential dose from DRPs at the MDA when discussing compliance with the dose criterion for license termination.

The scanning methods that are effective for identifying areas of elevated residual radioactivity in surface soil typically need to be adjusted to ensure an adequate sensitivity for DRPs, which usually approximate point sources rather than area sources. Licensees should acknowledge in their LTPs or DPs that, if there is reason to suspect DRPs may be present in a survey unit, then suitable survey methods, instructions, and training will occur to ensure that risk-significant DRPs will be identified and removed. The following sections discuss one method to determine which DRPs may be considered risk significant and determine scan minimum detectability activity (MDA) for DRPs.

4.1.1. Survey Objectives Appropriate for Discrete Radioactive Particles

The objectives of a DRP survey should include identification and collection of risk-significant DRPs, if present. Depending on the source, size, and radioactivity makeup of the DRP(s), the potential exposure from DRPs can be assessed to identify a corresponding activity level that the survey should be able to detect with adequate sensitivity. For particles primarily constituted of Co-60 and Cs-137, a required detection sensitivity of 0.5 microcurie (μCi) may be initially assumed. If the radioactivity makeup and size of the DRPs are not known before the survey, then obtaining this information from a statistically significant number of identified particles may also be an objective of the survey. This information could then be used to retroactively determine the sensitivity of the survey, the risk significance of the DRPs, and consider whether additional effort is needed to identify and remediate risk-significant DRPs.

The level of confidence needed in the survey should also be considered because, if the risk significance is high enough or if site conditions make it challenging to conduct surveys for risk-significant DRPs, more than one survey of the impacted areas may be necessary to provide sufficient confidence in the results. For this reason, it is normally necessary to note the location where a DRP has been identified and post it on a site map to ensure that the boundaries of the DRP survey are sufficient to encompass the range of the release or range of any secondary transport mechanism. The amount of cover over any identified DRP should also be noted as it may indicate how long ago a release happened or if secondary transport may have occurred.

4.1.2. Discrete Radioactive Particle Scanning/Identification Methods

This section presents some generally accepted scanning survey or other identification methodologies for DRPs in the outside environment. Typically, surveys for DRPs at nuclear power plants involve the use of gamma detectors, such as 2-inch x 2-inch sodium iodide (NaI) detectors, with significant surveyor vigilance involved. For example, the surveyor progresses at approximately 0.25 meters per second with a high incidence of false positives (so must often

halt to investigate perceived elevated count rates). Some licensees may choose to improve the surveyor's efficiency by using headphones to minimize noise conflicts with the instrument's auditory signals or detector collimation to reduce background. Also, in the case of challenging field conditions increasing the likelihood of human error, more than one survey could be performed to provide additional assurance of the accuracy of the surveys. Oak Ridge Institute for Science and Education (ORISE) was contracted to develop methodologies for evaluating scanning survey sensitivities (ORISE 2023 (ML24004A133)). Table 4-1 gives examples of the estimated sensitivities that can be achieved using a 2-inch x 2-inch NaI detector for selected radionuclides and varying levels of soil cover. Figures 4-1a and 4-1b illustrate the optimistic and pessimistic source configurations that were evaluated. Licensees are expected to use instrumentation that provides adequate sensitivity to the radionuclides of concern at their site and to estimate the range of detector sensitivity in their LTP or DP.

Some general conclusions on scanning surveys for DRPs are apparent from the ORISE report referenced above. For instance, scanning surveys should be conducted expeditiously following a DRP release to minimize the potential for secondary movement of the DRPs or mixing with soil or other materials. Unique survey methods may need to be considered if DRPs are present under surface soil or bodies of water (i.e., they are shielded) or are otherwise hard to detect. For example, it may be practical to engage technology for bulk screening or sorting of radioactive material in soil. Also, to maximize the "pessimistic scenario" sensitivity, significant diligence by the surveyor is necessary to perform the survey as slowly as practical, with the detector as close to the surface as practical, and to stop and investigate all perceived momentary increases in the count rate. Once a DRP is identified via scanning, the particle should be collected promptly, as it may be subject to secondary transport mechanisms and/or be difficult to re-identify later.

Another example of a screening technique employed in the past is the use of in situ gamma spectroscopy to look for indications of plant-related radionuclides. The sensitivity of such a survey would be determined by conservatively modeling the DRP at the edge of the detector's field of view. If there is an indication that a DRP may be present, additional investigation of the area in the detector's field of view would be needed using handheld detectors. In addition to its evaluation of handheld detector sensitivity, ORISE studied the sensitivity of using in situ gamma ray spectrometry for detecting discrete area sources (ORISE 2006). NUREG-1507, Rev 1, (NRC 2020) "Minimum Detectable Concentrations with Typical Radiation Survey for Instruments for Various Contaminants and Field Conditions," includes a summary of the conclusions from this study.

Table 4-1 DRP Scan MDA for Various Scan Conditions and a Surveyor Velocity of 0.25 m/s (μCi)

Particle Depth in Soil	Radionuclide and Ground-to-Detector Distance							
	Co-60		Cs-137		Th-232		Am-241	
	7.5 cm	10 cm	7.5 cm	10 cm	7.5 cm	10 cm	7.5 cm	10 cm
Optimistic Scenario (Figure 4-1a)								
Surface	0.09	0.11	0.16	0.21	0.04	0.05	0.35	0.45
7.5 cm	0.15	0.18	0.33	0.38	0.12	0.13	-	-
15 cm	0.31	0.34	0.77	0.85	0.29	0.33	-	-
30 cm	1.2	-	4.2	-	-	-	-	-
Pessimistic Scenario (Figure 4-1b)								
Surface	0.37	0.38	0.74	0.75	0.19	0.19	1.7	1.7
7.5 cm	0.70	0.67	1.8	1.6	0.66	0.61	-	-
15 cm	1.2	1.1	3.4	3.2	1.3	1.3	-	-
30 cm	3.4	-	14.1	-	-	-	-	-

Source: ORISE 2023, "SCAN MDA's for DRPs Technical Report," Final Technical Report, December 2023 (ML24004A133)
"–" indicates that the calculation shows the DRP cannot be identified during scans. All values are rounded to two significant digits or the hundredth position.

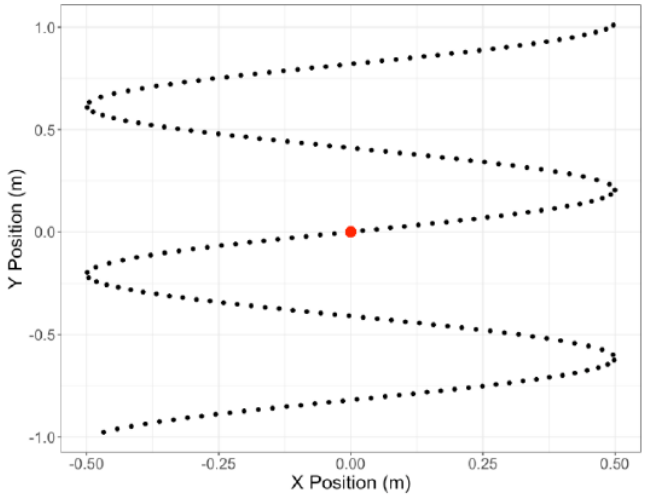

Figure 4-1a. Optimistic Scenario

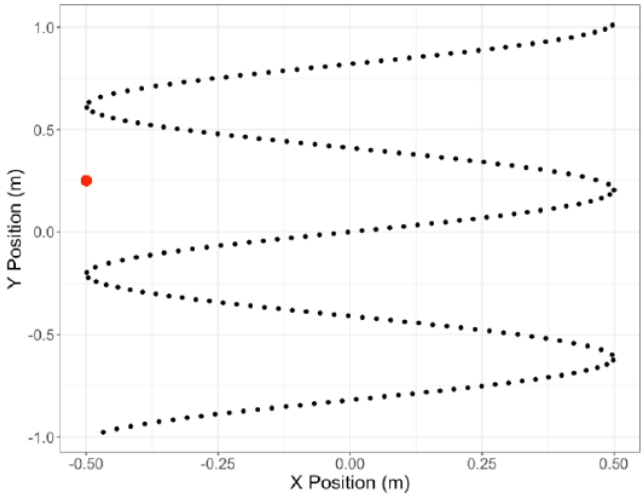

Figure 4-1b. Pessimistic Scenario

The optimistic scenario in figure 4-1a depicts a survey in which the detector passes directly over the source, and figure 4-1b shows a pessimistic scenario in which the detector is the furthest distance from the surveyor transect. The surveyor is walking in the +Y direction and swinging the NaI detector in the ±X-axis. The surveyor is standing in the direction of the +Z axis. (The red dot indicates source location.)

DRPs may also be identified when investigating small “hot spots” that are initially detected during any scanning survey. If a small volume of material can be collected that appears to completely resolve the detected radioactivity, one can then try and determine whether the activity can be isolated by repeatedly splitting the collected material until only a particle or artifact containing the radioactive material exists. If very small, the particle(s) may be best secured using a strip of packing tape, or similar material, by pressing the sticky surface to the particle(s). Once the particle(s) are collected, the tape can be folded to secure the particle(s) within the sticky surface, and the tape can then be easily handled and sent for further analyses. This collection may best be performed in a controlled environment or by a laboratory. Before a licensee submits such samples, laboratories should be notified of the potential that DRPs are present as they may need to take special precautions.

4.1.3. Documenting Contamination Events, Surveys, and Remediation of Discrete Radioactive Particles

As previously discussed, the licensee should document DRP contamination events in its 10 CFR 50.75(g) file, or corrective action system, or both. When preparing the HSA, the licensee should consult the 10 CFR 50.75(g) file to incorporate past events and to plan area remediation and/or characterization as appropriate. Remediation action support surveys of relevant decommissioning operations and routine contamination control surveys should similarly be part of the effort to identify a DRP release before it can spread to the environment. However, unplanned events do occur that may result in a release to the environment, and the licensee should then take corrective actions, consistent with this ISG, to identify, collect, and disposition any DRPs. The licensee should take corrective actions expeditiously to minimize the potential for secondary transport of DRPs, as well as the potential for DRPs to be covered by soil disturbing operations. All identified DRPs should be removed from the site so that no known DRPs remain. As previously mentioned, removal and disposition of all identified DRPs should be considered an ALARA practice in the site decommissioning operations. Licensees should establish a threshold for identifying DRPs based on risk significance. They should ensure their survey instruments and methodologies will identify DRPs at that level, and then they should remove all DRPs they find (even if they happen to be below the “risk significant” threshold).

Once scanning surveys have identified a DRP, the licensee should note the location on a site map to ensure that the scanning survey encompasses the areal range of the DRP release. Assuming that the DRPs all originate from a single event or source, a statistically significant number of the particles should be analyzed to determine the radionuclides involved and the size range of the particles and to allow a subsequent assessment of the potential exposure to a member of the public after license termination. The depth below the surface where the particle was collected should also be noted as it may indicate how long ago the release happened and how much secondary movement may have occurred. Pictures of the particles and artifacts collected are also useful to communicate with NRC staff about the potential hazard. Once a licensee has completed its DRP surveys, the NRC may perform a confirmatory survey. If there is sufficient confidence that the DRPs have been remediated, the site can then be evaluated in a more standard manner, in accordance with NUREG-1575 and NUREG-1757. As a best practice, the 10 CFR 50.75(g) file should document the successful demonstration of remediation. If this is a new spill/release since the HSA, summarizing in the FSS report can provide a more complete site history for the licensee, the NRC, and other interested parties (potentially years after license termination).

If a FSS of an area potentially impacted by a DRP release is being planned, the DQOs for the survey should incorporate assurance of adequate sensitivity to identify any risk-significant

DRPs. If DRPs are identified during the FSS, the FSS report should discuss the circumstances of the discovery and the risk significance of potential exposure to DRPs on the site. If the DRP survey is conducted after the FSS, it may be submitted as a supplement to the FSS report for the survey unit.

4.1.4. Demonstrating Applicability of New Detection Technologies

If the licensee wants to use novel or unique methods for DRP surveys, other than those discussed in this ISG, field trials and testing should be performed to demonstrate the survey method's applicability and sensitivity before full implementation, and the NRC should be informed to ensure that the methods are generally acceptable. The field testing should include comparison of the sensitivity of the technique to that of handheld field instrument scanning. The licensee should clearly identify the purpose of the data being generated (whether it is a replacement for another approach or is supplementary, with positive findings resulting in additional investigation), how the method meets the DQOs and MQOs, and the range of conditions for which the method is appropriate. Licensees may also consider requesting approval of novel approaches from the NRC ahead of an LTP or DP submission to avoid delays in the LTP or DP review.

4.2. Assessing Potential Dose from Discrete Radioactive Particles

The evaluation of the potential dose from DRPs differs from the evaluation of the potential dose from diffuse contamination, because the potential exposure scenarios can differ. For example, licensees typically perform environmental pathways modeling to develop derived concentration guideline levels based on the assumption that the residual radioactivity at a site is diffuse throughout the environmental media. A commonly assumed scenario for evaluating potential dose from diffuse contamination in soil is the resident farmer scenario. In this scenario, the residual radioactivity is assumed to cover a large area with the radioactivity being distributed throughout the environmental media with multiple potential routes of exposure. However, for DRPs, the contamination is assumed to be concentrated in a smaller particle or object, and the size of the particle would be too small to support activities such as gardening or farming. DRPs are not typically assessed as being incorporated into other environmental media because they are generally assumed to be insoluble in water.

4.2.1. Assessing Public Risk from Discrete Radioactive Particles

The unrestricted release criteria in 10 CFR 20.1402 state that a site will be considered acceptable for unrestricted use if the residual radioactivity that is distinguishable from background radiation results in a TEDE to an average member of the critical group that does not exceed 25 mrem (0.25 millisievert) per year, including that from ground water sources of drinking water, and the residual radioactivity has been reduced to levels that are ALARA. NUREG-1757, Volume 2, Revision 2, provides guidance on assessing the hypothetical exposure to diffuse contamination in soil or structures.

A "less likely but plausible" (LLBP) category of hypothetical considerations is found in guidance in NUREG-1757, Volume 2, Revision 2, Table 5.1, "Comparison and Description of Scenario Terms Used in this Guidance." An LLBP scenario should be considered if an unlikely but plausible situation arises, whether it be a potential land use that is not justified for defining the average member of the critical group or when materials can be considered generally inaccessible for an average member of the critical group except in unlikely scenarios.

For an LLBP scenario to be used to risk-inform the regulatory decision for license termination, the licensee should demonstrate that the risk to the public after license termination is not significant. Consistent with NUREG-1757, Volume 2, Revision 2, this has previously been interpreted as a scenario that has a low probability of occurrence (i.e., is not likely) and would not exceed the public dose limit of 100 mrem/year TEDE. If DRPs are found and removed via the survey and sampling process, then there should be no known DRPs remaining at a site after completion of the surveys. However, human error or other extenuating circumstances during DRP remediation are possible and could result in a low probability of encountering a DRP. Thus, licensees may elect to treat the possibility of encountering a DRP as an LLBP condition to risk-inform the decision for site release.

Because surveys for DRPs should be effective in identifying and removing the particles from surface soil, there is only a small probability that relatively lower activity particles (i.e., harder to detect particles) may remain in surface soil after license termination. While larger particles may remain undetected in subsurface soil, the probability of subsurface particles may be negligible if timely surveys were performed following the release of the particles or if no soil-disturbing activities have occurred since the release.

If DRPs are identified in open land survey units during FSSs, then the FSS report should contain an assessment of the potential dose for public exposure to a DRP. The licensee should use site-specific knowledge of the surrounding land uses to identify an appropriate scenario to address potential exposure to a hypothetical DRP remaining at the site and demonstrate that the potential exposure would both meet the public dose limits and otherwise pose no significant risk to the public. The activities most likely to result in resuspension of DRPs in air (i.e., soil-disturbing activities) should be considered, such as farming if particles are mostly limited to the surface soil layer, or construction if the particles are in subsurface soil.

In addition to being less than the public dose limit, the potential dose evaluated for a hypothetically exposed member of the public should include SDE exposures to the skin and “localized” dose equivalent (LDE), which is similar to SDE exposures but to internal organs if a particle is either inhaled or ingested. While there is a current occupational exposure limit of 50 rem for SDE (see 10 CFR 20.1201(a)(2)(ii)), LDE is a relatively novel concept, and the NRC staff considers it appropriate to have a similar restriction on DRP exposure of internal organs (i.e., 50 rem). A 50-rem exposure for SDE and LDE is considered to be protective of deterministic effects as documented in the rulemaking for the SDE regulations and is significantly less than the threshold for ulceration in the upper respiratory tract or gastrointestinal (GI) tract as documented in a recent technical report (Hamby et al. 2022). In addition, the committed effective dose equivalent (CEDE) dose from ingestion of a particle should also be considered if inhalation or ingestion is assessed as a hypothetical pathway of exposure. The NRC staff recognizes that limits for the public have not been established for these types of exposures but believes that any such estimated exposures should provide confidence that no deterministic effects will occur in a member of the public. Table 4-2 shows the likely pathways for exposure and the dose limits that should be evaluated for DRP LLBP scenarios.

Table 4-2 Exposure Pathways and Applicable Dose Limits for Less Likely but Plausible Scenarios Involving DRPs

Exposure Pathway	Dose Limit
Inhalation	100 mrem TEDE 50 rem LDE
Ingestion	100 mrem TEDE 50 rem LDE
In-contact skin exposure	100 mrem TEDE 50 rem SDE
Noncontact external exposure	100 mrem TEDE

The NRC has contracted research to develop dose conversion factors for selected radionuclides and particle sizes that may be used to conduct a first-order assessment of potential exposures through these pathways. “Dose Coefficients for Discrete Radioactive Particles (DRP),” dated May 1, 2023, is the technical report containing these dose conversion factors (Hamby et al. 2023).

4.2.2. Potential Exposure Scenarios and Pathways for Discrete Radioactive Particles

For DRPs located on or near the ground surface, a potential dose assessment should consider four potential pathways of exposure: (1) external effective dose equivalent (EDE) from DRPs located on the ground, (2) external EDE and SDE from DRPs attached to skin or clothing, (3) internal CEDE from inhalation of DRPs, and (4) internal CEDE from ingestion of DRPs. In addition, SDE from DRP exposure in contact with skin and LDE from DRP exposure should be considered for tissues in the upper respiratory tract (URT) and in the GI tract to assess whether deterministic effects may occur.

The potential dose from a DRP via these pathways depends on the size and activity of the particle. When evaluating the potential dose associated with DRPs, it is necessary to consider both the aerodynamic equivalent diameter and the spherical equivalent diameter of the particle. It should be noted that this is not the activity median aerodynamic diameter, which infers a distribution of particles being present. Also, the spherical equivalent diameter is referred to for DRPs because they are typically not spherical in shape, and the difficulties in accurately estimating the volume of an irregularly shaped small object are recognized.

An aerodynamic equivalent diameter of 10 micrometers (μm) is generally accepted as the largest respirable particle size. However, particle sizes of up to 100 μm aerodynamic equivalent diameter may be capable of being temporarily suspended in air and may even become temporarily lodged in the upper nasal passages before being cleared. Particles in the nasal passages may be cleared either by being expelled from the body (e.g., by blowing the nose) or passing through the GI tract after swallowing. Particle sizes greater than 100 μm aerodynamic equivalent diameter are generally considered too heavy to be suspended in air and would fall out and not be considered a risk for any portion of the respiratory tract.

Another exposure pathway typically considered for a DRP is ingestion. DRPs released during operational periods of nuclear power plants can be very small; mostly less than 250 μm equivalent diameter which is slightly smaller than a typical grain of table salt. However, in the case of concrete chips or cuttings or pieces of activated metal, the size can vary significantly up to several centimeters equivalent diameter. The NRC staff believes it unreasonable to assume that someone would unintentionally or unknowingly ingest a hard metal or concrete object

greater than about one-fifth of a cubic centimeter in volume (i.e., greater than 7256 µm spherical equivalent diameter, which is a spherical diameter of approximately one-half that associated with the volume of a cubic centimeter).

Another route of potential exposure is external exposure from a particle being "stuck" on someone's skin or clothing. Again, a practical consideration of the particle size is needed because larger concrete or metal chips are unlikely to be unintentionally stuck on someone's skin or clothing for any significant length of time. Of course, even these larger particles may pose an external hazard to someone who comes in contact with them; thus, licensees should estimate the potential for someone being unintentionally in contact with a particle even if it is not "stuck" to them.

The particle size is also of interest because, assuming a fixed concentration of activity (e.g., µCi/cm^3), the radioactivity present is proportional to the volume of the material. Since volume is proportional to the cube of the particle's spherical radius (as demonstrated by the equation for the volume of a sphere, below), as the particles become smaller, the amount of radioactivity present decreases exponentially:

$$Volume_{Sphere} = \frac{4}{3}\pi r^3$$

4.2.3. Assessing the Potential Exposure from Discrete Radioactive Particles

The following discussions describe a conservative methodology for estimating the potential exposure to a hypothetical DRP that may be encountered after license termination at a site where a DRP release to the environment previously occurred. Much of the information is adapted from a technical report from NRC-supported research (Hamby et al. 2023). While the following sections briefly describe the methods used and present the results of the research, additional detail is available in the referenced report. The research is based on an assumption of spherical particles, although DRPs are seldom perfectly spherical, which would impact the assumed isotropic emissions from the particle. However, the uncertainties associated with the DRP geometry and emissions are expected to be of minimal consequence. Attachment A to this ISG presents an example of an assessment of hypothetical exposure to DRPs.

4.2.3.1. Estimating the Particle Size

For most situations involving a DRP, the only significant information that may be easily quantifiable is the radioactivity associated with the particle. For the greatest accuracy, analysis of a DRP should involve dissolution so that the solute can then be placed in an appropriate container of standard geometry for gamma spectroscopy. Wet chemistry methods may also be used to isolate the harder-to-detect radionuclides and then quantify them through liquid scintillation or other appropriate analytical methods. However it is achieved, an estimate of the total radioactivity in a DRP should be available. This may also help identify the source of the material and root cause of any release. These data should be made available for a statistically significant number of particles, if practical, to estimate the range of particle sizes and types of particles present.

Assuming that the size of the DRP is not easily determined, a conservative assumption will be that a particle is very small. If the source of the release is known, it may be possible to determine the radioactivity concentration in the material from which the DRP(s) originated. If the

source of the particle is unknown, it is likely easiest to refer to site characterization data to estimate the highest concentration of activity at the site for the type of material of concern. For metal DRPs at a nuclear power plant (e.g., DRPs primarily containing Co-60 and Ni-63), this will usually be materials associated with either the reactor vessel or its internal equipment or fixtures. For activated concrete at a nuclear power plant (e.g., DRPs primarily containing radioisotopes of europium), the material of concern would usually be portions of the bioshield wall closest to the reactor or floor under the reactor. For fuel fleas, a concentration of easily measured fission products may be estimated from the records associated with spent fuel removed from the reactor. It is preferrable to use site-specific characterization data for an estimation of maximum radioactivity concentration in likely materials, although the NRC does have technical reports that may assist in estimating a conservative concentration of activity in certain materials (e.g., NUREG/CR-0130 (NRC 1978), NUREG/CR-3474, (PNNL,1984), NUREG/CR-7227 (NRC 2016)).

Once the activity and conservative concentrations are known or conservatively assumed, it is simple to divide the measured DRP activity by the concentration in materials to estimate the total volume of the DRP. For simplicity, if one assumes the volume is that associated with a sphere, the spherical equivalent diameter can be estimated using the equation below:

$$d_e = 2 * r_e = 2 * \sqrt[3]{\frac{3 * \pi * Volume_{sphere}\,(cm^3)}{4}}$$

where: d_e = spherical equivalent diameter (cm)
r_e = spherical equivalent radius (cm)

Note that 1 cm equals 10,000 µm.

As previously noted, for particles of approximately 100 µm spherical equivalent diameter or less, it is also necessary to estimate the aerodynamic equivalent diameter. This can be accomplished by converting the spherical equivalent diameter to an aerodynamic equivalent diameter as described by equation D.5 in International Commission on Radiological Protection (ICRP) Publication 66, “Human Respiratory Tract Model for Radiological Protection,” issued in 1994 (ICRP 1994), which, in cases where the slip correction ratio approaches unity, reduces to the equation presented below:

$$d_{ae} = d_e \sqrt{\frac{\rho}{\chi}}$$

where: d_{ae} is the aerodynamic equivalent diameter
d_e is the spherical equivalent diameter
ρ is the density of the material
χ is the particle shape factor (for typical densities a particle shape factor of 1.5 suffices for compact, irregularly shaped particles) (ICRP 66, section D.13.1)

Once the spherical equivalent diameter and aerodynamic equivalent diameter have been estimated, the potential pathways of exposure can be assessed. The following discussions are adapted from a technical report based on NRC-supported research (Hamby et al. 2023). While a brief description of the methods employed and results is presented here, the referenced report contains additional detail.

4.2.3.2. Assessing Potential Exposure from Particles Located in the Upper Respiratory Tract

Particles less than 10 μm aerodynamic equivalent diameter are "respirable," meaning they can be breathed deep into the lung, and particles less than 100 μm aerodynamic equivalent diameter are "inhalable" and can be captured in the inhalation airstream and lodged in the nasal vestibule or nasopharynx. Particles greater than about 100 μm aerodynamic equivalent diameter are generally assumed to fall out of the air quickly and are too large to be inhaled (https://www.worksafe.qld.gov.au/safety-and-prevention/hazards/hazardous-exposures/hazardous-dusts, as shown on August 2, 2024). Assessment of particles in this ISG is limited to sizes greater than 10 μm spherical equivalent diameter.

For inhalation, deposition of DRPs is assumed to be limited to the upper regions of the respiratory tract (i.e., extrathoracic compartments). Extrathoracic transfer is assigned a constant fractional rate of 1 day $(d)^{-1}$ for transfer to the environment from the anterior nose (i.e., removal) and 100 d^{-1} for transfer to the esophagus from the posterior nasal passages, pharynx, mouth, and larynx (ICRP 1994). Potential DRPs deposited in the posterior nasal passages, pharynx, mouth, and larynx are assumed to be transferred quickly (i.e., in minutes) to the GI tract (ICRP 2006). Transfer to the esophagus at a constant fractional rate of 100 d^{-1} implies very short residence times for particles deposited in these regions. For dose estimation purposes, particulate material can be assumed to remain in the anterior nose for roughly 1 day, with a maximum residence time for a DRP in the anterior nose assumed here to be 2 days. A CEDE coefficient was not determined for the inhalation pathway because DRP particles are assumed to be too large to get past the URT. These particles would likely be expelled to the environment (e.g., by nose blowing) or swallowed and then follow the ingestion pathway model.

Tables 4-3 and 4-4 present dose coefficients (DCs) applicable for estimated LDE exposure, as well as EDE exposure for particles in the URT. The DCs for LDE were determined for a particle resting on a flat surface with air behind the source (i.e., VARSKIN+ backscatter correction implemented). DCs for the EDE from internal stationary particles were determined using PiMAL (Phantom with Moving Arms and Legs) software and Monte Carlo N-Particle® Version 6 (MCNP6®). The EDE is calculated for a DRP in the URT by simulating energy deposition in various organs and assigning radiation weighting factors and summing organ doses using the ICRP 26/30 tissue -weighting factors[4]. Multiple locations were assessed, with the maximum EDE reported. This EDE is not a calculation of internal dosimetry (no biokinetics are considered) but rather a calculation of weighted DE to various organs of the body from a single particle stuck in the URT (i.e., not different than the consideration of a particle stuck on the upper torso).

[4] The tissue-weighting factor is a relative measure of the risk of stochastic effects that might result from irradiation of that specific tissue. It accounts for the variable radiosensitivities of organs and tissues in the body to ionizing radiation.

Table 4-3 LDE Coefficients for a DRP Stationary in the Upper Respiratory Tract

Upper Respiratory Tract DE Coefficients (Sv/Bq h)							
Diameter (μm)	10	20	50	100	200	500	1000
Stellite 6	(Z = 33; ρ = 8.4 g/cm^3)						
Co-60	1.3E-06	1.2E-06	8.0E-07	4.7E-07	2.6E-07	1.3E-07	7.7E-08
Inconel 718	(Z = 29; ρ = 8.2 g/cm^3)						
Ni-59	2.0E-08	2.0E-08	2.0E-08	2.0E-08	2.0E-08	1.9E-08	1.7E-08
Ni-63	4.1E-10	2.1E-10	8.6E-11	4.4E-11	2.2E-11	9.0E-12	4.5E-12
Regulatory Concrete	(Z = 10; ρ = 2.3 g/cm^3)						
Fe-55	1.8E-08	1.9E-08	1.9E-08	1.9E-08	1.9E-08	1.8E-08	1.7E-08
Co-60	1.3E-06	1.3E-06	1.2E-06	1.0E-06	7.4E-07	3.8E-07	2.0E-07
Ba-133	2.3E-07	2.1E-07	1.5E-07	1.3E-07	1.2E-07	8.6E-08	5.4E-08
Eu-152	1.1E-06	1.1E-06	9.5E-07	7.8E-07	6.2E-07	4.2E-07	2.7E-07
Eu-154	2.5E-06	2.3E-06	2.1E-06	1.7E-06	1.4E-06	9.1E-07	5.7E-07
Fuel Fragment	(Z = 88; ρ = 11 g/cm^3)						
Sr-90*	1.7E-06	1.7E-06	1.4E-06	9.2E-07	5.0E-07	2.0E-07	8.9E-08
Cs-137*	1.7E-06	1.7E-06	1.5E-06	1.1E-06	6.6E-07	2.7E-07	1.3E-07
Eu-154	2.1E-06	1.8E-06	1.3E-06	9.6E-07	6.0E-07	2.7E-07	1.3E-07
Eu-155	4.6E-07	3.0E-07	1.4E-07	7.3E-08	4.0E-08	1.9E-08	1.2E-08
Pu-238	3.2E-09	3.2E-09	3.2E-09	3.0E-09	2.9E-09	2.6E-09	2.3E-09
Pu-239	1.8E-09	1.8E-09	1.7E-09	1.7E-09	1.6E-09	1.5E-09	1.4E-09
Pu-240	3.1E-09	3.0E-09	3.0E-09	2.9E-09	2.7E-09	2.4E-09	2.2E-09
Pu-241	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Am-241	1.7E-08	1.5E-08	1.3E-08	1.3E-08	1.2E-08	1.0E-08	9.2E-09
Cm-244	2.4E-09	2.4E-09	2.4E-09	2.3E-09	2.2E-09	2.0E-09	1.8E-09
Welding Rod	(Z = 74; ρ = 19 g/cm^3)						
Th-232	5.7E-09	4.0E-09	2.9E-09	2.5E-09	2.2E-09	1.9E-09	1.6E-09
Ra-228	4.5E-09	4.5E-09	4.5E-09	4.3E-09	4.1E-09	3.6E-09	3.2E-09
Ac-228#	2.0E-06	1.9E-06	1.6E-06	1.2E-06	7.3E-07	3.0E-07	1.4E-07
Th-228	2.6E-04	2.6E-04	2.6E-04	2.6E-04	2.6E-04	2.6E-04	2.6E-04
Ra-224	1.2E-03	1.2E-03	1.2E-03	1.2E-03	1.2E-03	1.2E-03	1.2E-03

Source: Hamby, D.M., et al., 2023, "Dose Coefficients for Discrete Radioactive Particles (DRP)," RCD Radiation Protection Associates, May 1, 2023 (ML23136A178).

* Including progeny contributions assumed to be in secular equilibrium with the parent.

\# Instantaneous dose rate at time zero.

Table 4-4 Maximum EDE Coefficients for a DRP in the Upper Respiratory Tract

Nuclide	EDE Coefficients (Sv/Bq h)
Stellite 6	
Co-60	8.8E-08
Inconel 718	
Ni-59	2.8E-09
Ni-63	0.0E+00
Regulatory Concrete	
Fe-55	2.6E-09
Co-60	8.8E-08
Ba-133	2.3E-08
Eu-152	4.1E-08
Eu-154	4.3E-08
Fuel Fragment	
Sr-90*	1.3E-06
Cs-137*	1.8E-08
Eu-154	4.3E-08
Eu-155	3.3E-09
Pu-238	1.3E-09
Pu-239	5.4E-10
Pu-240	1.2E-09
Pu-241	0.0E+00
Am-241	5.9E-09
Cm-244	8.5E-10
Welding Rod	
Th-232	8.9E-10
Ra-228	8.6E-10
Ac-228#	3.4E-08
Th-228	1.2E-09
Ra-224	4.4E-10

Source: Hamby, D.M., et al., 2023, "Dose Coefficients for Discrete Radioactive Particles (DRP)," RCD Radiation Protection Associates, May 1, 2023 (ML23136A178).

* Including progeny contributions assumed to be in secular equilibrium with the parent.

\# Instantaneous dose rate at time zero.

Note: use of ICRP 26/30 tissue weighting factors

A conservative assessment of the dose (LDE) resulting from a DRP hypothesized to be located in the URT can be obtained by multiplying the activity (Bq) of the DRP, the appropriate DC (Sv/Bq-h) for the spherical equivalent diameter, and an estimate of the time (h) it may be present. If the spherical equivalent diameter is not close to one of the tabulated values, the

assessment should use a more conservative DC as smaller particles generally have less self-shielding. Similarly, for the EDE estimate, one simply takes the product of the activity associated with the DRP, the estimated time a DRP is present in the URT, and the dose conversion factor. It should be noted that there is a probability that a DRP in the URT is transferred to the GI tract. To assess that case, the total EDE will be the EDE associated with the URT in addition to the CEDE estimated for the GI tract. LDE is applicable only for the tissue in contact with the DRP (like SDE for evaluating skin exposures) and is not summed for multiple organs.

4.2.3.3. Assessing Potential Exposure from Particles in the Gastrointestinal Tract

Assessments of an ingested particle may involve consideration of both mobile and immobile particles. In the GI tract, the small and large intestines are assumed to be filled with typical intestinal content, and therefore, electron backscatter will contribute to localized tissue dose. DCs are provided per unit time (dose rate) so that radiation dose can be calculated for various exposure assumptions. While there have been documented occasions when a DRP has been "stuck" for several days in the GI tract, the NRC staff considers that situation to be unlikely. Evaluation of a hypothetical LDE exposure would appropriately consider the more likely situation in which a particle is only present or stuck in the organ with the highest mean residence time (i.e., the lower large intestine for 24 hours.). The lower large intestines have a greater mean residence time than the small intestines (24 hours versus 4 hours); however, the target tissues are at different depths, so the DCs vary. For this reason, the LDE DCs for both organs are presented. Tables 4-5 and 4-6 show the LDE DCs for a stationary DRP located in the small intestine and large intestine.

The LDEs for particles stuck on the inner wall of the small and large intestines were calculated using the Skin Dose module in VARSKIN+ v1.1. The dose was estimated to an infinitely thin 1 cm^2 disk at a tissue depth of 14 mg/cm^2 (140 µm) in the small intestine and a depth of 29 mg/cm^2 (290 µm) in the large intestine for spherical DRPs between 10 and 1,000 µm in diameter. Because of the physical separation between villi in the small intestine, DRPs greater than about 100 µm are not as likely to become lodged in the villi. The dose averaging area of 1 cm^2 was used to mimic the approximate maximum size of an ulcer.

Table 4-5 LDE Coefficients for a DRP in the Small Intestine

Small Intestine DE Coefficients (Sv/Bq h)							
Diameter (μm)	10	20	50	100	200	500	1,000
Stellite 6	(Z = 33; ρ = 8.4 g/cm^3)						
Co-60	4.6E-07	4.1E-07	2.7E-07	1.7E-07	1.0E-07	6.1E-08	4.5E-08
Inconel 718	(Z = 29; ρ = 8.2 g/cm^3)						
Ni-59	1.1E-08	1.1E-08	1.1E-08	1.1E-08	1.1E-08	1.1E-08	1.0E-08
Ni-63	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Regulatory Concrete	(Z = 10; ρ = 2.3 g/cm^3)						
Fe-55	8.8E-09	8.8E-09	8.8E-09	8.8E-09	8.8E-09	8.8E-09	8.6E-09
Co-60	5.0E-07	4.8E-07	4.8E-07	3.6E-07	2.6E-07	1.3E-07	8.2E-08
Ba-133	7.1E-08	7.1E-08	7.1E-08	7.1E-08	6.7E-08	4.7E-08	3.1E-08
Eu-152	4.5E-07	4.4E-07	4.4E-07	3.9E-07	3.6E-07	2.7E-07	1.9E-07
Eu-154	1.1E-06	1.1E-06	1.1E-06	9.1E-07	8.0E-07	5.8E-07	3.8E-07
Fuel Fragment	(Z = 88; ρ = 11 g/cm^3)						
Sr-90*	1.1E-06	1.0E-06	8.1E-07	5.2E-07	2.8E-07	1.2E-07	5.7E-08
Cs-137*	1.2E-06	1.2E-06	9.4E-07	6.8E-07	4.2E-07	1.9E-07	9.4E-08
Eu-154	1.0E-06	9.2E-07	7.5E-07	5.6E-07	3.7E-07	1.8E-07	9.6E-08
Eu-155	4.6E-08	3.3E-08	1.8E-08	1.1E-08	7.5E-09	5.2E-09	4.2E-09
Pu-238	1.8E-09	1.7E-09	1.7E-09	1.7E-09	1.6E-09	1.4E-09	1.3E-09
Pu-239	7.6E-10	7.5E-10	7.5E-10	7.3E-10	7.0E-10	6.4E-10	5.6E-10
Pu-240	1.6E-09	1.6E-09	1.6E-09	1.6E-09	1.5E-09	1.4E-09	1.2E-09
Pu-241	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Am-241	7.0E-09	7.0E-09	6.9E-09	6.7E-09	6.4E-09	5.7E-09	5.0E-09
Cm-244	1.3E-09	1.3E-09	1.3E-09	1.3E-09	1.2E-09	1.1E-09	9.3E-10
Welding Rod	(Z = 74; ρ = 19 g/cm^3)						
Th-232	1.3E-09	1.3E-09	1.3E-09	1.3E-09	1.2E-09	1.1E-09	9.6E-10
Ra-228	2.5E-09	2.5E-09	2.5E-09	2.4E-09	2.3E-09	2.1E-09	1.8E-09
Ac-228#	1.2E-06	1.2E-06	1.1E-06	8.1E-07	5.2E-07	2.3E-07	1.1E-07
Th-228	1.7E-09	1.7E-09	1.7E-09	1.6E-09	1.6E-09	1.4E-09	1.2E-09
Ra-224	1.3E-08	9.9E-09	4.9E-09	2.7E-09	1.5E-09	7.6E-10	4.8E-10

Source: Hamby, D.M., et al., 2023, "Dose Coefficients for Discrete Radioactive Particles (DRP)," RCD Radiation Protection Associates, May 1, 2023 (ML23136A178).

* Including progeny contributions assumed to be in secular equilibrium with the parent.

\# Instantaneous dose rate at time zero.

Table 4-6 LDE Coefficients for a DRP in the Large Intestine

Large Intestine DE Coefficients (Sv/Bq h)							
Diameter (μm)	10	20	50	100	200	500	1,000
Stellite 6	(Z = 33; ρ = 8.4 g/cm^3)						
Co-60	1.2E-07	1.1E-07	7.8E-08	5.9E-08	4.7E-08	3.7E-08	3.2E-08
Inconel 718	(Z = 29; ρ = 8.2 g/cm^3)						
Ni-59	6.1E-09	6.1E-09	6.1E-09	6.1E-09	6.1E-09	6.1E-09	6.0E-09
Ni-63	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Regulatory Concrete	(Z = 10; ρ = 2.3 g/cm^3)						
Fe-55	4.0E-09	4.0E-09	4.0E-09	4.0E-09	4.0E-09	4.0E-09	4.0E-09
Co-60	1.3E-07	1.2E-07	1.1E-07	9.6E-08	7.4E-08	5.0E-08	3.9E-08
Ba-133	4.7E-08	4.7E-08	4.6E-08	4.4E-08	3.9E-08	2.6E-08	1.8E-08
Eu-152	2.5E-07	2.5E-07	2.4E-07	2.3E-07	2.2E-07	1.8E-07	1.3E-07
Eu-154	5.3E-07	5.3E-07	5.1E-07	4.9E-07	4.5E-07	3.5E-07	2.5E-07
Fuel Fragment	(Z = 88; ρ = 11 g/cm^3)						
Sr-90*	5.3E-07	5.2E-07	4.1E-07	2.7E-07	1.4E-07	5.9E-08	2.9E-08
Cs-137*	6.4E-07	6.2E-07	5.3E-07	4.0E-07	2.6E-07	1.2E-07	6.3E-08
Eu-154	5.1E-07	4.9E-07	4.4E-07	3.5E-07	2.4E-07	1.3E-07	7.0E-08
Eu-155	4.0E-09	3.5E-09	3.0E-09	2.8E-09	2.7E-09	2.5E-09	2.3E-09
Pu-238	1.3E-09	1.3E-09	1.2E-09	1.2E-09	1.2E-09	1.1E-09	9.6E-10
Pu-239	5.0E-10	5.0E-10	5.0E-10	4.9E-10	4.8E-10	4.4E-10	3.9E-10
Pu-240	1.2E-09	1.2E-09	1.2E-09	1.1E-09	1.1E-09	1.0E-09	9.0E-10
Pu-241	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Am-241	5.0E-09	5.0E-09	4.9E-09	4.8E-09	4.7E-09	4.3E-09	3.8E-09
Cm-244	9.1E-10	9.1E-10	9.0E-10	8.9E-10	8.6E-10	7.9E-10	6.9E-10
Welding Rod	(Z = 74; ρ = 19 g/cm^3)						
Th-232	9.9E-10	9.8E-10	9.8E-10	9.6E-10	9.4E-10	8.7E-10	7.7E-10
Ra-228	1.8E-09	1.8E-09	1.8E-09	1.8E-09	1.7E-09	1.6E-09	1.4E-09
Ac-228#	7.7E-07	7.9E-07	7.3E-07	5.7E-07	3.7E-07	1.7E-07	8.8E-08
Th-228	1.3E-09	1.3E-09	1.3E-09	1.2E-09	1.2E-09	1.1E-09	9.8E-10
Ra-224	4.1E-09	2.9E-09	1.5E-09	8.8E-10	5.8E-10	3.7E-10	2.8E-10

Source: Hamby, D.M., et al., 2023, "Dose Coefficients for Discrete Radioactive Particles (DRP)," RCD Radiation Protection Associates, May 1, 2023 (ML23136A178).

* Including progeny contributions assumed to be in secular equilibrium with the parent.

\# Instantaneous dose rate at time zero

A conservative estimate of the LDE from a "nonstationary" particle can be obtained as the product of the DRP activity, the mean residence time in the organ (24 hours in the lower large intestine or 4 hours in the small intestine), and the dose coefficient (DC) coinciding with the spherical equivalent diameter of the particle. If the particle size is in between values in the tables above, conservatively use the next smaller diameter particle.

The technical report from which the DCs above originated also includes values for estimating the EDE assuming a DRP is hypothesized to be stationary for an extended period. However, the NRC staff does not feel that consideration of such a situation is pertinent for a hypothetical assessment of a nonstationary particle. Instead, the CEDE DC should be used for estimating dose via the values presented in tables 4-7 and 4-8.

Calculations of CEDE following ingestion of DRPs were made using version 5.0.1 of the Integrated Modules for Bioassay Analysis (IMBA) code. The CEDE coefficients were independent of DRP size and were assumed to follow the ICRP GI tract model (ICRP 1979), with the use of ICRP 26/30 tissue-weighting factors.

Except for fuel fragments, DRPs are assumed to have zero translocation to the body fluids ($f_1 = 0$). The CEDE coefficients calculated here assume that the radioactivity moves with intestinal content, and nothing is transferred to body fluids (table 4-9). The CEDE coefficients published in Federal Guidance Report (FGR) No. 11, "Limiting Values of Radionuclide Intake and Air Concentration and Dose Conversion Factors for Inhalation, Submersion, and Ingestion," issued in 1988 (Eckerman et al. 1988), are based on the GI tract model described in ICRP 30, "Limits for Intakes of Radionuclides by Workers," issued in 1979 (ICRP 1979). These coefficients were developed assuming that there is nonzero translocation of radionuclides to the body fluids ($f_1 > 0$). There is some evidence that irradiated fuel fragments are partially soluble in the fluids of the stomach and small intestine (ICRP 2017, 2019) and will therefore follow the biokinetics that allow for translocation to the body fluids.

Table 4-7 CEDE Coefficients for Ingested DRPs

	CEDE Coefficient (Sv/Bq)
Stellite (Z = 33; ρ = 8.4 g/cm^3)	
Co-60	1.8E-09
Inconel (Z = 29; ρ = 8.2 g/cm^3)	
Ni-59	2.9E-11
Ni-63	7.1E-11
NRC Concrete (Z = 10; ρ = 2.3 g/cm^3)	
Fe-55	2.4E-11
Co-60	1.8E-09
Ba-133	5.2E-10
Eu-152	1.2E-09
Eu-154	1.9E-09
Thoriated Welding Rod (Z = 74; ρ = 19 g/cm^3)	
Th-232	3.3E-09
Ra-228	2.2E-09
Ac-228	3.9E-10
Th-228	9.7E-09
Ra-224	1.8E-08

Source: Hamby, D.M., et al., 2023, "Dose Coefficients for Discrete Radioactive Particles (DRP)," RCD Radiation Protection Associates, May 1, 2023 (ML23136A178).

Fuel fragment CEDE coefficients (table 4-8, first column) were taken as the FGR 11 coefficient reported for the maximum (most limiting) f_1 value. While ICRP Publication 137, "Occupational Intakes of Radionuclides: Part 3," issued in 2017 (ICRP 2017), and ICRP Publication 141, "Occupational Intakes of Radionuclides: Part 4," issued in 2019 (ICRP 2019), provide CEDE coefficients for fuel fragments containing the radionuclides, they are based on the human alimentary tract model in ICRP Publication 100, "Human Alimentary Tract Model for Radiological Protection," issued in 2006 (ICRP 2006), not the ICRP 30 GI tract model. Translocation of

radionuclides into the body fluids in ICRP 100 is specified by the alimentary tract transfer factor, f_A, instead of the f_1 value as given for the GI tract model described in ICRP 30. All IMBA CEDE coefficients were calculated using ICRP 26/30 tissue-weighting factors.

The use of a nonzero f_1 value assumes that the ingested radionuclide is available for translocation to the body fluids at the specified rate. Given that this assumption may not be valid for a single DRP that has not completely disintegrated in the stomach and small intestine contents, CEDE coefficients were computed in IMBA for fuel fragments using 10 percent and 1 percent of the maximum f_1 value in FGR 11, denoted with $FGR_{0.1}$ and $FGR_{0.01}$, respectively. Coefficients were also calculated assuming zero translocation to the body fluids for fuel fragment radionuclides to provide a lower bound.

Table 4-8 CEDE Coefficients for Ingested Fuel Fragment DRPs

CEDE Coefficient (Sv/Bq)				
Fuel Fragment (Z = 88; ρ = 11 g/cm^3)				
		Varying f_1 values		
	FGR 11[a]	FGR $11_{0.1}$[bc]	FGR $11_{0.01}$[c]	$f_1 = 0$[d]
Sr-90	3.9E-08	5.3E-09	2.2E-09	2.0E-09
Cs-137	1.4E-08	2.6E-09	1.4E-09	1.3E-09
Eu-154	2.6E-09	1.9E-09	1.9E-09	1.9E-09
Eu-155	4.1E-10	3.0E-10	3.0E-10	3.0E-10
Pu-238	8.7E-07	7.7E-08	1.2E-08	4.6E-09
Pu-239	9.6E-07	8.5E-08	1.3E-08	4.3E-09
Pu-240	9.6E-07	8.5E-08	1.3E-08	4.3E-09
Pu-241	1.9E-08	1.7E-09	1.8E-10	2.2E-11
Am-241	9.8E-07	7.7E-08	1.3E-08	4.8E-09
Cm-244	5.5E-07	4.8E-08	9.2E-09	4.8E-09

a. FGR 11 CEDE coefficient for highest listed f_1 value
b. IMBA CEDE coefficient using f_1 value equal to 10% of FGR 11 maximum f_1 value
c. IMBA CEDE coefficient using f_1 value equal to 1% of FGR 11 maximum f_1 value
d. IMBA CEDE coefficient using f_1 value equal to zero

Source: Hamby, D.M., et al., 2023, "Dose Coefficients for Discrete Radioactive Particles (DRP)," RCD Radiation Protection Associates, May 1, 2023 (ML23136A178).
Note: use of ICRP 26/30 tissue weighting factors

The CEDE dose from a DRP can be estimated as the product of the activity of the DRP and the applicable DC in tables 4-7 and 4-8. The solubility of fuel fragments in the GI tract is not well established, so bounding estimates of the potential exposure should be made by using the DCs for the 10 percent and 0 translocation values in the table.

4.2.3.4. Assessing Potential Exposure from Particles on Skin

The SDE for particles on the skin at no specific location were calculated using the SkinDose module in VARSKIN+ v1.1 (table 4-9). To be consistent with NRC regulations (10 CFR 20.1201), the SDE was estimated for an infinitely thin 10 cm^2 disk at a depth of

7 milligrams (mg)/cm^2 (70 μm) in unit-density tissue. If it is necessary to average to a smaller disk (e.g., 1 cm^2), a modified DC could be roughly approximated by a factor equal to the ratio of averaging areas (e.g., 10 cm^2/1 cm^2 = 10); the DC for 1 cm^2 averaging will be approximately 10 times that of the DC for 10 cm^2 averaging. A spherical source geometry was assumed, and backscatter factors were applied to account for air above a source directly on the skin.

Table 4-9 SDE Coefficients for a DRP on the Skin Surface

	SDE Coefficients (Sv/Bq h)						
Diameter (μm)	10	20	50	100	200	500	1000
Stellite 6	(Z = 33; ρ = 8.4 g/cm^3)						
Co-60	9.8E-08	8.8E-08	6.0E-08	3.7E-08	2.2E-08	1.2E-08	8.9E-09
Inconel 718	(Z = 29; ρ = 8.2 g/cm^3)						
Ni-59	1.5E-09	1.5E-09	1.6E-09	1.6E-09	1.7E-09	1.7E-09	1.6E-09
Ni-63	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Regulatory Concrete	(Z = 10; ρ = 2.3 g/cm^3)						
Fe-55	1.3E-09	1.3E-09	1.4E-09	1.4E-09	1.5E-09	1.5E-09	1.5E-09
Co-60	9.9E-08	9.7E-08	8.9E-08	7.6E-08	5.6E-08	3.0E-08	1.8E-08
Ba-133	1.1E-08	9.9E-09	9.5E-09	9.4E-09	9.3E-09	7.3E-09	5.0E-09
Eu-152	7.6E-08	7.5E-08	6.8E-08	5.9E-08	5.0E-08	3.8E-08	2.8E-08
Eu-154	1.8E-07	1.7E-07	1.5E-07	1.3E-07	1.1E-07	8.1E-08	5.7E-08
Fuel Fragment	(Z = 88; ρ = 11 g/cm^3)						
Sr-90*	1.4E-07	1.4E-07	1.2E-07	7.6E-08	4.2E-08	1.7E-08	8.5E-09
Cs-137*	1.5E-07	1.5E-07	1.2E-07	9.3E-08	5.8E-08	2.6E-08	1.4E-08
Eu-154	1.6E-07	1.4E-07	1.1E-07	8.1E-08	5.4E-08	2.7E-08	1.5E-08
Eu-155	2.3E-08	1.5E-08	7.2E-09	4.0E-09	2.3E-09	1.3E-09	9.0E-10
Pu-238	2.4E-10	2.4E-10	2.5E-10	2.6E-10	2.6E-10	2.5E-10	2.3E-10
Pu-239	1.1E-10	1.1E-10	1.2E-10	1.3E-10	1.3E-10	1.2E-10	1.1E-10
Pu-240	2.2E-10	2.3E-10	2.4E-10	2.5E-10	2.5E-10	2.3E-10	2.1E-10
Pu-241	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Am-241	1.0E-09	1.0E-09	1.0E-09	1.1E-09	1.1E-09	9.8E-10	9.1E-10
Cm-244	1.8E-10	1.8E-10	1.9E-10	2.0E-10	2.0E-10	1.9E-10	1.7E-10
Welding Rod	(Z = 74; ρ = 19 g/cm^3)						
Th-232	1.7E-10	1.8E-10	1.8E-10	1.9E-10	1.9E-10	1.8E-10	1.6E-10
Ra-228	3.3E-10	3.4E-10	3.6E-10	3.7E-10	3.7E-10	3.4E-10	3.2E-10
Ac-228#	1.7E-07	1.6E-07	1.4E-07	1.1E-07	6.9E-08	3.2E-08	1.7E-08
Th-228	1.1E-09	6.5E-10	4.0E-10	3.3E-10	2.8E-10	2.4E-10	2.2E-10
Ra-224	2.2E-09	1.8E-09	8.8E-10	4.8E-10	2.6E-10	1.3E-10	8.2E-11

Source: Hamby, D.M., et al., 2023, "Dose Coefficients for Discrete Radioactive Particles (DRP)," RCD Radiation Protection Associates, May 1, 2023 (ML23136A178).

* Including progeny contributions assumed to be in secular equilibrium with the parent.

\# Instantaneous dose rate at time zero.

DCs of EDE for DRPs resting on the mid-torso were calculated using PiMAL coupled with MCNP6®. PiMAL uses a computational human phantom when coupled with MCNP for the assessment of radiation dose to various organs. MCNP6® is a general-purpose Monte Carlo radiation-transport code designed to track many particle types over broad ranges of energies. Many different combinations of particle placement were investigated to determine the maximum EDE coefficient reported for a DRP on the skin surface. The EDE was calculated using the

tissue-weighting factors in ICRP Publication 26, “Recommendations of the ICRP,” issued in 1977 (ICRP 1977), and ICRP Publication 30 (Part 1) (ICRP 1979), as required by 10 CFR Part 20. Tables 4-9 and 4-10 contain DCs for stationary DRPs on the skin surface.

Table 4-10 Total Body EDE DCs for a DRP of a Given Size Stationary on the Skin of the Chest

EDE DCs (Sv/Bq h)	
Nuclide	External Chest Surface
Stellite 6	
Co-60	5.8E-10
Inconel 718	
Ni-59	4.6E-13
Ni-63	0.0E+00
Regulatory Concrete	
Fe-55	4.1E-14
Co-60	5.8E-10
Ba-133	5.5E-09
Eu-152	1.3E-08
Eu-154	1.4E-08
Fuel Fragment	
Sr-90	1.7E-12
Cs-137	1.4E-10
Eu-154	3.1E-10
Eu-155	8.4E-10
Pu-238	2.7E-11
Pu-239	1.0E-11
Pu-240	2.5E-11
Pu-241	0.0E+00
Am-241	3.5E-10
Cm-244	2.7E-11
Welding Rod	
Th-232	1.4E-11

Source: Hamby, D.M., et al., 2023, “Dose Coefficients for Discrete Radioactive Particles (DRP),” RCD Radiation Protection Associates, May 1, 2023 (ML23136A178).

Note: use of ICRP 26/30 tissue weighting factors

As in other methods to assess potential exposure from DRPs, an estimate of the potential SDE or EDE exposure is simply the product of the activity of the DRP, the estimate of the time (in hours) a DRP is present on the skin, and the DC from the approximate sized DRP column. For EDE estimates, the calculation was conservatively done, assuming a point source with no self-shielding, so no particle size is presented. Larger size particles or objects may conservatively be assessed using the smaller sized column’s DCs as increasing self-shielding

occurs as the particle or artifact gets larger. This is the reason the DCs can be observed gradually decreasing as the diameter of the particle increases.

4.3. Addressing Discrete Radioactive Particles in License Termination Plans and Decommissioning Plans

In 10 CFR 50.82, the NRC specifies the information that must be included in the LTP. The regulation states, in part, that the LTP should include a site characterization, plans for site remediation, and detailed plans for the final radiation survey. As required in 10 CFR 50.82(a)(9)(ii)(C) and Subpart E of 10 CFR Part 20, the LTP should discuss in detail how facility and site areas will be remediated to meet the NRC's release criteria. This includes a detailed description of the techniques that will be used to remove or remediate surface and subsurface soils, ground water, and surface water and sediments. Licensees should note that DRPs can become an issue even at sites with no history of fuel failure or releases during operation, given that DRPs may be produced and released during the segmentation or dismantling of RV internals and other contaminated piping, equipment, or components. Often, the HSA and site characterization activities are completed before or concurrent with segmentation and dismantling activities that may contribute to the spread of contamination. In multiple cases, contamination events have occurred after the LTP license amendment request was submitted to the NRC and, in some cases, after the LTP was approved.

Licensees' LTPs and DPs should address, at a high level, DRP surveying and remediation as well as how to generally control, monitor for, and remediate contamination during decommissioning operations. Licensees should commit to collecting and dispositioning any DRPs resulting from licensed activities that are identified in the environment. Such commitments should be incorporated into site procedures early in the decommissioning process. If the licensee elects not to include such commitments in its submittals, the NRC may issue license conditions to address DRP surveys, potential corrective actions, and documentation. The NRC staff considers DRP contamination to be a contamination control issue or a radiation protection program issue that should generally be resolved before a survey unit is turned over for FSS. If DRPs are known or suspected to have been released in a survey unit, then the FSSP should incorporate appropriate survey instrumentation and methods to demonstrate that no risk-significant DRPs are present. If a DRP is detected and removed during or after the FSS, the FSS report should note this and incorporate an LLBP discussion of the potential dose to a member of the public from a hypothetical exposure to a DRP. The NRC staff is likely to consider such situations for confirmatory surveys, and will ensure that proper DQOs are established.

5. Conclusions

DRPs have been known to result from some plant operations and major component replacement outages, requiring diligent contamination control and monitoring to remain compliant with 10 CFR 20.1501. The decommissioning landscape introduces new contamination control challenges, such as changing building layouts and airflow, opening enclosed spaces, and dewatering areas. During active decommissioning, the spread of DRPs has resulted from material movement from buildings, debris piles, or stockpiles; waste handling and transport; and inclement weather impacts. Survey designs (DQOs and MQOs) may need to be adjusted to ensure adequate DRP detection. If a licensee identifies DRPs in the environment, the licensee should remediate the DRPs through its contamination control program as opposed to relying on the FSS to identify DRPs.

There have been instances of untimely or inadequate surveys conducted after cross-contamination involving DRPs. Corrective actions to identify and collect DRPs in the environment should be performed expeditiously once a release has occurred to minimize the spread or covering of contamination and maximize the probability of detecting DRPs during surveys. It should be considered an ALARA practice to collect and disposition any DRP resulting from licensed activities identified during a licensee's surveys of the environment. Discovery of DRPs during decommissioning operations and during confirmatory surveys has resulted in increased regulatory oversight and additional work to assess the presence and risk significance of the particles. Consequently, this has caused significant delays in the license termination process and the expenditure of unplanned resources.

Licensees that have a history of DRPs or that may generate DRPs during decommissioning should also have a strong contamination control program designed to prevent environmental contamination events involving DRPs. The program should include both the use of appropriate contamination control methods (e.g., containment, ventilation, and fixatives) and routine surveys around potential sources of DRPs, to provide reasonable assurance that DRPs are not being unknowingly released and spread. Licensees should enter DRP contamination events into the site's corrective action program and should consider retaining the program findings and disposition of such events in the 10 CFR 50.75(g) file to inform future decommissioning activities. Such information may assist licensees in determining the appropriate survey(s) to be performed for identification, remediation, verification, and documentation that DRPs have been remediated.

Licensees should address future actions upon potential discovery of DRP contamination in the environment as a commitment in their LTP or DP submittals. These types of commitments should address, at a high level, the DQOs and MQOs that will be considered for surveys supporting license termination. The submittals should discuss the survey instrumentation, methods, and techniques that will be used to provide reasonable assurance that risk-significant DRPs are removed from the environment. If DRPs are identified and removed after a survey unit has been released for an FSS, then the FSS report should include an LLBP discussion as to why the public risk from exposure to DRPs is acceptable for license termination.

Whenever DRPs are identified during any phase of operations or decommissioning, the licensee should notify the NRC's assigned project manager and inspector to ensure knowledge of the potential issue is shared. Documenting the DRP characteristics, survey design (such as MDAs), extent of contamination, and remediation efforts will be useful in demonstrating that the licensee has identified and remediated the contamination. This may reduce both regulatory uncertainty and the time needed to assess the site status at the time of license termination. In all cases where DRPs are found after FSSPs have been approved, the NRC staff will assess whether a license amendment is needed to ensure that adequate surveys are performed.

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Attachment A
Example Dose Assessment for Potential Discrete Radioactive Particles

This attachment presents one example of an assessment for potential discrete radioactive particles (DRPs) that may be present at a site after a release of DRPs.

A.1. Hypothetical Risk Assessment for Discrete Radioactive Particles

Although remedial actions were taken to eliminate DRPs at a given site, an assessment was performed of the DRPs collected during the most recent DRP surveys at the site to evaluate the dose that would result if not all DRPs were identified and removed due to human error during scanning or other circumstances. The most recently collected DRPs were assumed to be representative for this assessment.

A hypothetical encounter with a DRP at the site after the partial site release was considered to be a "less likely but plausible scenario" (LLBP), as described in Table 5.1, "Comparison and Description of Exposure Scenario Terms Used in this Guidance," of NUREG-1757, "Consolidated Decommissioning Guidance," Volume 2, Revision 2, "Characterization, Survey, and Determination of Radiological Criteria," issued July 2022 (Agencywide Documents Access and Management System Accession No. ML22194A859). The LLBP scenario dose evaluations are not analyzed for compliance but rather for risk-informed decision-making. For LLBP scenarios, U.S. Nuclear Regulatory Commission (NRC) guidance calls for considering land use scenarios that are plausible and based on historical uses but that are not likely within the next 100 years based on trends and area land use plans (e.g., rural use of property currently in an urban setting). These scenarios are usually site specific. For the site under consideration, the LLBP site-specific scenario used to evaluate exposure to DRPs is the construction worker scenario. This is because additional industrial or commercial development at the site is plausible once the site is released for unrestricted use, and it is believed such activity would pose the highest probability for exposure to a DRP, in the unlikely event one was present, due to the soil disturbance associated with construction. It is believed to be very unlikely that a DRP would be present at any time because both the licensee and NRC contractors conducted extensive DRP hand scanning, using appropriate techniques.

Confirmatory surveys identified 12 DRPs, and the licensee's supplemental extent of condition survey identified 1 DRP. All 13 DRPs were either activated metal (primarily cobalt (Co)-60 activity) or activated concrete (primarily europium (Eu)-152/Eu-154 activity). The 10 activated metal particles ranged in Co-60 activity from approximately 0.014 microcuries (μCi) to 0.38 μCi. Nickel (Ni)-63 may also be present in these particles at slightly greater activity levels than Co-60, but because Ni-63 is a very low-energy beta emitter and contained in what is considered an environmentally insoluble matrix, Ni-63 would not contribute in any significant way to potential dose. The three activated concrete samples ranged in Co-60 activity from 5.7×10^{-4} μCi to 3.0×10^{-3} μCi. The Eu-152/Eu-154 activities in these particles ranged from 4.6×10^{-3} μCi/2.9×10^{-4} μCi to 6.1×10^{-2} μCi/4.4×10^{-3} μCi.

To assess the potential impact of the recovered DRPs, initially one has to consider the sizes of the DRPs collected. The size of the DRPs was assessed by assuming the materials were the most concentrated of their types identified during the site characterization efforts, as discussed in the licensee's response to requests for additional information and reviews of requests for

partial site release related to the size of DRPs. For the activated metal, the concentration was based on reactor internal component characterization of the Unit 1 baffle plates with a Co-60 concentration of 4.06 x 10^{+4} µCi per cubic centimeter (cm^3). For activated concrete, the highest Co-60 concentration was in core B102110-CJFCCV-001 at 1.09 x 10^{+3} picocuries (pCi) per gram (g) with an estimated concrete density of 2.35 g/cm^3. Using these concentrations and the Co-60 activity estimates of the DRPs, the activated metal DRPs were estimated to range in size from 87 micrometers (µm) to 262 µm spherical equivalent diameter and from 202 µm to 605 µm aerodynamic equivalent diameter. The concrete DRPs ranged from 0.22 cm^3 to 1.2 cm^3 in volume. Examples of the calculations used are shown below:

$$Volume\ (cm^3) = {Activity_{Co\text{-}60}}/{Max\ Concentration_{Co\text{-}60} * \rho}$$

where ρ is the density of the material when the maximum concentration is in units of pCi/g. For concrete, ρ is assumed to be 2.35 g/cm^3. For the smallest amount of Co-60 (therefore the smallest concrete particle), the calculation was as follows:

$$Volume\ (cm^3) = {570\ pCi}\Big/{1{,}909\ \frac{pCi}{g} * 2.35\ \frac{g}{cm^3}} = 0.223\ cm^3$$

For the metal particles, the spherical volume was calculated by simply dividing the activity by the concentration (the maximum concentration was based on site characterization data). The spherical equivalent diameter was calculated by determining the radius of the sphere:

$$Volume\ (cm^3) = \frac{4}{3}\pi r^3$$

$$r = \sqrt[3]{\frac{3}{4\pi} Volume\ (cm^3)}$$

$$diameter\ (d_e) = 2 * r$$

An additional step was then needed to determine the aerodynamic equivalent diameter of the smaller particles, because particles of greater than 100 µm aerodynamic equivalent diameter are most likely to fall out of the air and not be inhaled. This was accomplished by converting the spherical equivalent diameter to an aerodynamic equivalent diameter, as described in equation D.5 in International Commission on Radiological Protection (ICRP) Publication 66, "Human Respiratory Tract Model for Radiological Protection," issued 1994:

$$d_{ae} = d_e \sqrt{\frac{\rho}{\chi}}$$

where d_{ae} is the aerodynamic equivalent diameter; d_e is the spherical equivalent diameter; ρ is the density of the material (8 g/cm^3 is assumed for steel); and χ is the particle shape factor (for typical densities, a particle shape factor of 1.5 suffices for compact, irregularly shaped particles; see section D.13.1 in ICRP Publication 66).

For the smallest amount of Co-60 in the activated metal particles, the calculations would be as follows:

$$Volume_{sphere} = {1.42E-2\ (\mu Ci)}\Big/{4.064\ E4\ \frac{\mu Ci}{cm^3}} = 3.5E-7\ cm^3$$

$$d_e = 2r = 2 * \sqrt[3]{\frac{3 * 3.5e-7\ (cm^3)}{4\pi}} = 0.0087\ cm = 87\ \mu m$$

$$d_{ae} = 87\ \mu m \sqrt{\frac{8}{1.5}} = 201\ \mu m$$

If any of the 13 DRPs that were removed were hypothetically to become resuspended due to construction work, the size of the DRPs, being greater than 100 µm aerodynamic equivalent diameter, would generally preclude any of the particles being inadvertently introduced into an individual's respiratory tract.[5] The activated concrete particles were also large enough to prevent inadvertent ingestion. For reference, a grain of table salt is commonly estimated to be about 300 µm along any side (equating to approximately 2.7 x 10^{-5} cm^3); the activated metal DRPs were all less than 300 µm in spherical diameter, while the concrete particles were estimated to be significantly larger. A cubic centimeter is often compared to the volume of a pea or a pencil eraser, and the smallest concrete particle was estimated to be 0.22 cm^3 in volume, which the NRC staffs consider large enough to not be inadvertently swallowed (note that the radius of a 1 cm^3 sphere is about 0.62 cm, while the radius of a 0.22 cm^3 sphere is about 0.37 cm).

Due to the size of the 13 DRPs found and removed at the site, the potential exposure scenarios considered for the activated metal DRPs involved either potentially ingestion or a particle being stuck on the skin for approximately 12 hours until being washed off, consistent with the 12-hour "time to first shower" concept described by the Defense Threat Reduction Agency (DTRA) in DTRA-TR-09-16, "Radiation Doses to Skin From Dermal Contamination," issued October 2010. The activated concrete particles (which were the size of small pebbles) were assessed as being in contact with the skin for 2 hours, which was considered conservative for a hypothetical scenario of a worker lying on the ground, possibly napping during a long lunch period. Using dose coefficients (ML23136A178), the hypothetical dose estimates were determined for the highest activity DRPs for each medium, as shown in table A-1.

Table A-1 Bounding Hypothetical Dose from Exposure to Most Activated Discrete Radioactive Particles

Most Activated Metal DRP		
Hypothetical Dose Category (Assumptions)	**Calculated Dose**	**Public Dose Limit (TEDE)***

5 "Particles greater than about 100 um [in diameter] are generally assumed to fall out of the air quickly and are too large to be inhaled (worksafe.qld.gov.au)," RCD Radiation Protection Associates, "Dose Coefficients for Discrete Radioactive Particles (DRP)," dated May 1, 2023 (ML23136A178).

EDE (located on upper torso for 12 hours)	9.9 mrem	100 mrem/y
CEDE (ingestion assumed)	2.6 mrem	100 mrem/y
Most Activated Concrete DRP		
EDE (in contact with skin on upper torso for 2 hours)	0.05 mrem	100 mrem/y

*TEDE is the sum of EDE and CEDE exposures when both an internal and external dose occur.

In table A-1, EDE is the effective dose equivalent from external exposure, assuming a DRP comes into contact with an individual's upper torso. It is a component of the total effective dose equivalent (TEDE), which has a public dose limit of 100 millirem per year (mrem/y). CEDE is the committed effective dose equivalent from internal exposure assuming a particle is ingested and passes through the gastrointestinal (GI) tract, consistent with reference man models (it should be noted that the particles were considered to be insoluble). CEDE is a component of TEDE, which has a public dose limit of 100 mrem/y.

To assist with a risk-informed consideration of DRP exposures, additional hypothetical exposures not generally considered applicable to meeting the unrestricted release decommissioning criteria were also assessed. Specifically, a hypothetical or skin dose equivalent (SDE), a defined dose term with limits established for occupational workers, was assessed. Also assessed was a hypothetical localized dose equivalent (LDE) exposure, a previously undefined dose term that is essentially the same as SDE but was recently used to evaluate dose within the GI tract for potential deterministic effects (e.g., ulceration). For the most activated metal particle, the calculated SDE for a 12-hour exposure and 10 cm^2 averaging area (consistent with guidance for assessing occupational exposure to hot particles) is 374 mrem. For the most activated concrete particle, which was assumed to be in contact with the skin for 2 hours and to have a 10 cm^2 averaging area, the calculated SDE exposure is 15 mrem. For comparison, the occupational dose limit for SDE is 50,000 mrem (see Title 10 of the *Code of Federal Regulations* 20.1201(a)(2)(ii)). It is noted that the occupational dose limit was established to be protective of deterministic effects, which would be the same for occupational workers as for the public. Similarly, the hypothetical LDE was estimated for the highest activity metal particle assuming a 24-hour exposure and 1 cm^2 averaging area in the lower large intestine/colon and was calculated to be 1,600 mrem. There is no regulatory limit for this term; however, the NRC staff considers it appropriate to compare it to the ulceration threshold of ~25 gray (~2,500,000 mrem (see ML23136A207)). It is apparent that the hypothetical SDE/LDE exposures are more than an order of magnitude below the deterministic effect thresholds of consideration.

Also assessed was the possibility that activity associated with a particle with an aerodynamic equivalent diameter of 100 µm might potentially result in a significant dose. Particles of this size are hypothesized to be capable of being inhaled and temporarily residing in the nasal cavity for a period that generally results in a higher dose than other means of exposure. It was determined that an activated metal particle with Co-60 activity of 1.75×10^{-03} µCi correlates to a 100 µm aerodynamic diameter based on the maximum concentrations reported at the site. When the hypothetical dose from this activity particle was assessed, the largest estimate was found to be approximately 9.2 mrem EDE, assuming a particle is "stuck" in the nasal cavity for 1 day then cleared through the GI tract. A similar calculation for activated concrete particles was not considered because the activity levels in a particle of 100 µm aerodynamic equivalent diameter

were essentially insignificant (e.g., <1 pCi Co-60 would be present) relative to any assessment criteria, even when using the maximum activity concentrations in concrete.

Also considered were the sensitivity of the scanning surveys performed and the hazards of any DRPs that may not have been identified and removed during the most recent scanning surveys. The Oak Ridge Institute for Science and Education (ORISE) report "Estimating Scan Minimum Detectable Activities of Discrete Radioactive Particles," issued December 2023 (ML24004A133), provides a range of likely DRP Co-60 activities that scanning consistent with ORISE methods would likely detect. Table 4.1 of the ORISE report provides a range of approximately 0.1 µCi to 0.7 µCi Co-60, depending on exactly how close to the detector path the particle is located and how deeply it is covered in soil. The values quoted are consistent with the conditions ORISE identified during its survey of the scanning speed and depth of particles in soil. ORISE identified and removed particles with a minimum activity of 0.014 µCi Co-60, suggesting that the true sensitivity could be much less than that estimated in the report. The highest activity DRP ORISE found at the site contained 0.38 µCi Co-60, which is slightly more than half of the upper limit of sensitivity in the report. No more than twice the dose calculated for the most active metal particle would be assessed (i.e., 19.8 mrem TEDE) if a particle at the upper range of estimated sensitivity were encountered, and the dose from exposure to that activity DRP would still be much less than the public dose limit (or dose thresholds for deterministic effects).

A.2. Example Assessment Conclusion

The particles identified and collected during the most recent scanning surveys at a licensee's site were assessed for hypothetical risk to a member of the public. Contractors and the licensee used appropriate hand-scanning techniques for DRPs over a majority of the site, so only DRPs that may have been missed due to human error or other extenuating circumstances may remain; thus, it is believed the probability of encountering a DRP at the site is very low. Because all calculated EDE/CEDE hypothetical doses were less than 100 mrem/y TEDE (the public dose limit), and other hypothetical dose estimates (SDE and LDE) were much less than what would be considered exceedance of any deterministic threshold, there is reasonable assurance that, in the very unlikely event that exposure to DRPs could occur at the site, any exposure would be consistent with the LLBP category of hypothetical considerations consistent with guidance in table 5.1 in NUREG-1757, Volume 2, Revision 2.

This conclusion, when combined with the fact that both the contractors and the licensee have made a significant effort to identify and remove DRPs from the site, demonstrates keeping radiation exposure as low as is reasonably achievable in practice. Further, because the primary radionuclides are Co-60 and Eu-152/154, the activity and potential dose associated with any remaining DRPs, if present, will reduce over time, consistent with the half-lives of these radionuclides (the half-life of Co-60 is 5.27 years, Eu-152 is 13.5 years, and Eu-154 is 8.59 years). As such, should anyone encounter a DRP at the site, the potential dose will significantly diminish over time.

A.3. Example References

Defense Threat Reduction Agency (DTRA). DTRA-TR-09-16, "Radiation Doses to Skin From Dermal Contamination," Fort Belvoir, Virginia, October 2010.

D.M. Hamby, C.D. Mangini, C.T. Rose, and R.R. Benke, 2023, RCD Radiation Protection Associates, Contractor Technical Report, "Dose Coefficients for Discrete Radioactive Particles

(DRP)" ML23136A178, May 1, 2023.

International Commission on Radiological Protection (ICRP). ICRP Publication 66, "Human Respiratory Tract Model for Radiological Protection," Pergamon Press, Oxford, United Kingdom, 1994.

NRC/RES/DSA, RCD Radiation Protection Associates, Renaissance Code Development, LLC, 2023. "Final DRP Ulceration Thresholds Contractor Technical Report, ML23136A207, September 15, 2022.

ORISE 2023, "SCAN MDA's for DRPs Technical Report," Final Technical Report, ML24004A133, December 2023.