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Technical Basis for Release of Materials from Radiological Control

Approvals

Written By: Carmen DuVall, UID:cduvall — Digitally signed by Carmen DuVall, UID:cduvall Date: 2022.03.18 10:29:49 -05'00' — Date: 03/18/2022

Carmen DuVall, Radiation Physicist

Reviewed By: Holly Hall, UID:hollyh — Digitally signed by Holly Hall, UID:hollyh Date: 2022.03.18 10:17:53 -05'00' — Date: 03/18/2022

Holly Hall, Radiation Physicist

Reviewed By: Wayne Schmitt — Digitally signed by Wayne Schmitt Date: 2022.03.18 11:59:03 -05'00' — Date: 03/18/2022

Wayne Schmitt, Radiation Physics Science Department Head

Reviewed By: Maddie Schoell, UID:maddiew — Digitally signed by Maddie Schoell, UID:maddiew Date: 2022.03.18 14:11:51 -05'00' — Date: 3/18/2022

Madelyn Schoell, Radiation Physics Operations Department Head

Reviewed By: Adam Olson, UID:aolson — Digitally signed by Adam Olson, UID:aolson Date: 2022.03.18 12:04:49 -05'00' — Date: 03/18/2022

Adam Olson, Radiation Physics Engineering Department Head

Approved By: Matthew Quinn — Digitally signed by Matthew Quinn Date: 2022.03.18 15:02:26 -05'00' — Date: 03/18/2022

Matthew Quinn, Senior Radiation Safety Officer

Revision History

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Technical Basis Document

1.0 Purpose

The purpose of this Technical Basis Document is to provide an acceptable approach for managing and dispositioning personal property, commonly referred to as materials and equipment (M&E), that may be radiologically impacted (mainly by radioactivation) by accelerator or radiation-generating device (RGD) operation. This document is Fermi National Accelerator Laboratory's (Fermilab's) implementation of DOE-STD-6004-2016 *Clearance and Release of Personal Property from Accelerator Facilities* [DOE 2016]. This Technical Basis for Release of Materials from Radiological Control describes Fermilab's program for unrestricted release of M&E that is characterized as having no detectable radioactivity other than natural background, based on 1) process knowledge, and 2) measurement protocols.

Personal property that is determined to have no detectable radioactivity other than natural background is not subject to radiological control and, therefore, can have unrestricted release. The purpose of unrestricted release is for off-site recycle, reuse, or disposal of M&E released from facility upgrades, dismantling projects, routine operations, or other activities. The potential dose to members of the public resulting from the release of these materials is well below that of the background radiation ubiquitous in the natural environment. Therefore, any health effects from release of these materials are indistinguishable from the health effects produced by naturally occurring background radiation.

2.0 Scope

The Fermilab clearance protocol for potentially activated M&E, including regulatory, administrative, technical, and operational elements, is described in this document.

The M&E defined in this document covers mainly solid metal, concrete, accelerator and RGD components (such as magnets, radiofrequency [RF] cavities, vacuum chambers, beam pipes, waveguides, cables, etc.), detector components (including the detectors, electronics, power supplies, etc.) and auxiliary components (such as racks, cabinets, supporting stands/tables, etc.). Materials used for shielding can also be released under this document.

This document addresses M&E from any area at Fermilab within which there was or is potential for volumetric activation and/or surface contamination of the material. Examples of these areas include accelerator tunnels with an accelerator or beam line operating at energies exceeding the activation thresholds of materials or contamination areas where surface contamination exists due to present or past facility operations. Other areas with the potential for activation (such as facilities that produce neutrons from targets or contain neutron-generating RGDs) also fall within the scope of this document.

Additional materials not covered in this document may be covered in a separate Radiation Physics Note, using the same process described in this document to characterize and release materials. Process knowledge, measurement methods, limitations, and bounding conditions that differ from those described in this document must be identified in separate material-specific or facility-specific documentation.

This document provides a basis for facility-specific material releases from projects that release significant amounts of M&E from radiological control, as well as routine activities that may release smaller amounts of such material from an operating beam line or other Radiological Area.

This document does NOT address the following:

1. Nonsolid materials (liquid, gas, powder, etc.), as the measurement protocols for nonsolid materials are different (often radiological characterization of nonsolid samples can be conducted in a practical and accurate manner using laboratory sample analysis methods),
2. Release of a site or real property, such a land,
3. Naturally occurring radioactive material (NORM) or technologically enhanced NORM,
4. Release of material containing detectable radioactivity other than natural background (i.e., material with residual radioactivity due to Fermilab operations). The relevant requirements in DOE Order 458.1, *Radiation Protection of the Public and the Environment,* will be followed if such a release option is sought by Fermilab.

M&E arising from a Fermilab area in which there is no potential for volumetric activation or surface contamination (e.g., areas with klystrons or x-ray RGDs) may be released without being subject to this document.

3.0 Facility and Background Information

3.1 Overview

Fermilab, located in DuPage and Kane Counties, Illinois, is a single-program laboratory dedicated to basic research in high-energy physics, related support activities, and associated scientific research programs. High-energy physics research involves the creation of new states of matter and the study of these states on a microscopic (atomic, nuclear, and sub-nuclear) scale. These states are created in the interaction of accelerated particle beams with other targets fixed in space or with other particle beams. A major portion of the research activities conducted at Fermilab involves the acceleration and delivery of particle beams to particle and nuclear physics experiments built and operated by collaborations of scientists assembled from many nations. These experiments and their constituent apparatus may also be calibrated by and used to study cosmogenic radiation.

Fermilab is a principal collaborator in the experimental program of the Large Hadron Collider at the European Organization for Nuclear Research (CERN) and a participant in other accelerator-related endeavors at other laboratories in the United States and elsewhere. New accelerator-related projects are being developed for the near, and intermediate, future. In addition, Fermilab is the base of support for several non-accelerator experiments in particle physics, particle astrophysics, and quantum information endeavors that utilize much of the same technology base as the accelerator-based research program. Some of these activities may be managed by Fermilab at locations that are not part of the government-owned Illinois site.

Fermilab also participates in applied physics and engineering activities designed to support the physics research program and to provide for transfer of technology developed at Fermilab to society at large. A major emphasis at the present time is accelerator development, materials science, detector technology, and quantum information systems directed toward future use both in the United States and in international collaborations. Important examples of transfer of technology include the research and development toward the advancement of the use of particle accelerators for routine medical treatments, and for radiobiological and medical research. Industrial applications of accelerators are also being pursued. Some of these involve partnerships with private enterprise and other institutions,

notably at the Illinois Accelerator Research Center (IARC), being developed on the Fermilab site. Other practical applications are being investigated.

Finally, education is an important part of Fermilab's mission. Educational activities range from elementary school and high school level activities at Fermilab to the sponsorship of graduate students working toward advanced degrees.

To accomplish its mission, Fermilab engages in the design, construction, commissioning, operation, and, as necessary, decommissioning of a large particle accelerator and related apparatus used for physics experiments. Components developed at Fermilab are used both on the Fermilab site and at other research facilities worldwide. Fermilab also operates related support facilities that provide equipment components for the physics experiments.

3.2 Accelerator Complex

Fermilab's main accelerator complex comprises four particle accelerators and beam transport lines: the Linac, Booster, Recycler, and Main Injector. Fermilab's accelerators and how they fit into the laboratory's accelerator complex are described below and shown in Figure 3.1.

Fermilab's linear accelerator, better known as the Linac, is a roughly 500-foot straight accelerator that brings proton beams up to energies of about 400 MeV before entering the Booster. Protons are accelerated through the Booster's approximately 1500-foot circumference ring to an energy of 8 GeV. The Booster provides low-energy neutrino beam for the Short Baseline Neutrino (SBN) program, as well as the Muon g-2 experiment and, in a few years, the Mu2e experiment. It also provides beam to the Recycler, a 2-mile-circumference ring where proton beams are combined into batches of protons to form a more intense beam. The Recycler provides beam for Muon g-2 (and, eventually, Mu2e) by circulating protons through the 500-meter-circumference Muon Delivery Ring, which decay into muons and are then routed into the storage ring for the Muon g-2 experiment.

The Recycler also provides a proton beam to the Main Injector. Situated directly beneath the Recycler in the same tunnel, the Main Injector ramps up proton beam from the Recycler from 8 GeV to 120 GeV. This high-energy beam is then sent to fixed-target experiments at the Fermilab Test Beam Facility (FTBF). The Main Injector also provides neutrino beams for the NOvA experiment, as well as the upcoming Long-Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE).

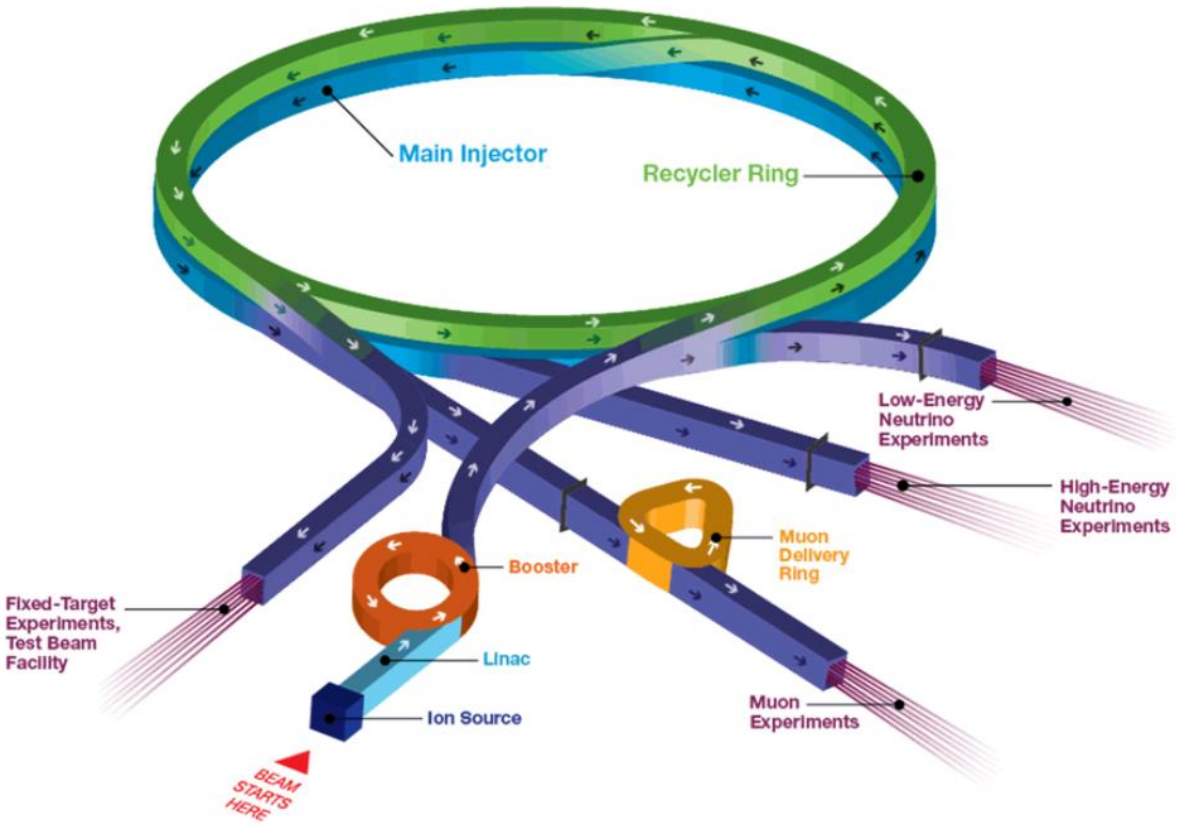

Figure 3.1 *Fermilab Accelerator Complex*

Hosted by Fermilab/Fermi Research Alliance (FRA), DUNE is an international experiment for neutrino science and proton decay studies. DUNE requires the construction and operation of a Near Detector on-site at Fermilab as well as a massive Far Detector located in two large caverns 4,850 feet below ground at the Sanford Underground Research Facility (SURF) in Lead, South Dakota. The LBNF project, also hosted by Fermilab, provides the beamline and the civil construction for the DUNE experiment, though the organization and management of LBNF are separate from that of the experiment. The SURF areas and facilities in Lead that are under Fermilab's direct management are collectively referred to as the LBNF Far Site (LBNF-FS).

In addition to the main accelerator complex, the Fermilab Accelerator Science and Technology (FAST) facility is a test bed for developing a fully-equipped R&D accelerator chain intended to support research and development of accelerator technology for the next generation of particle accelerators. Electrons are accelerated through a 125-meter linear accelerator, called the electron injector, to an energy of 150 MeV before heading into the Integrable Optics Test Accelerator (IOTA). The 40-meter-circumference IOTA accelerates electrons from the FAST electron injector and uses them to test new accelerator technologies and the physics of beams.

Radiological work is conducted in the radiation fields produced by the accelerators, as well as with manufactured sources and materials radio-activated by the accelerated beams. The dominant component of radiological exposure, in terms of the radiation dose to the environment or members of the public at Fermilab, involves prompt radiation produced by accelerator operations. Radioactive

sources are utilized for calibration purposes and as important components of the particle detectors. Radioactive materials are sometimes incorporated as part of the experimental apparatus and beamline components. Work with all these sources of radiation is a part of routine operations at Fermilab. Radioactive waste is generated during these operations. Collection and preparation of such waste for its transport to DOE-approved disposal sites is also conducted at Fermilab. Other shipments of radioactive materials are made to and from the Fermilab site in accordance with applicable transportation regulations.

A comprehensive environmental monitoring program managed in accordance with DOE requirements, notably DOE Order 458.1, *Radiation Protection of the Public and the Environment*, and accepted national standards in the context of an Environmental Radiation Protection Program (ERPP) is an important part of Fermilab's Environment, Safety, and Health (ES&H) program. Fermilab also participates in environmental monitoring that addresses environmental concerns related to past practices in compliance with regulatory agency requirements.

4.0 Definitions

ALARA (As Low As Reasonably Achievable): An approach to radiation protection to manage and control releases of radioactive material to the environment, and exposure to the work force and to members of the public, so that the levels are as low as is reasonably achievable, taking into account societal, environmental, technical, economic, and public policy considerations. ALARA is not a specific release or dose limit but a process which has the goal of optimizing control and management of releases of radioactive or non-radioactive material to the environment and potential doses so that they are as far below the public dose limit as reasonably achievable [adapted from DOE Order 458.1 definition].

Authorized limit: A limit on the concentration or quantity of residual radioactive material on surfaces or within property that has been determined to be consistent with DOE directives, including ALARA requirements. An authorized limit may also include conditions or measures that limit or control the disposition of property [adapted from DOE Order 458.1 definition].

Background: Radiation from:

- NORM that has not been technologically enhanced,
- Cosmic sources,
- Global fallout as it exists in the environment (such as from the testing of nuclear explosive devices),
- Radon and its progeny in concentrations or levels existing in buildings or the environment that have not been elevated as a result of current or prior activities, and
- Consumer products containing nominal amounts of radioactive material or producing nominal amounts of radiation.

Clearance (of property): The removal of property that contains or may contain residual radioactive material from DOE radiological control under 10 CFR Part 835 and DOE Order 458.1 for unrestricted release.

Clearance protocol: A set of processes and rules for determining the disposition of material, which includes three elements: clearance criteria, process knowledge and measurement methods.

Confirmatory measurement: Additional radiological measurement that is used to supplement surface surveys. Confirmatory measurements may include gamma spectrometry in the field, laboratory analysis of representative samples of the item using high-purity germanium (HPGe) detectors, portal gate monitors, bulk monitoring systems, or other means. Confirmatory measurement is a best management practice and is conducted, as warranted, using a graded approach based on considerations of process knowledge and ALARA.

Controlled Area: Any area to which access is managed by or for DOE to protect individuals from exposure to radiation and/or radioactive material as defined by 10 CFR Part 835.

Critical level (L_C): In counting statistics, the critical level is the count (or count rate) in a zero-mean count distribution having a defined probability (α) of being exceeded. In other words, it is the measured result at which one can decide whether the result indicates detection. This level is associated with determining if a measurement is indistinguishable from background (IFB).

Critical concentration: The critical concentration is the L_C corrected for detector efficiency and other factors to yield an estimate of the radioactivity concentration. The critical concentration has units of pCi/g.

Detection limit (L_D): The smallest amount of radioactivity (in pCi/g for volumetric radioactivity measurements or dpm/100 cm^2 for surface activity) that can be detected and quantified by a measurement method. The L_D may also be called the minimum detectable activity (MDA) or minimum detectable concentration (MDC). Statistically, the detection limit is based on the mean net count from a sample having a specified probability of escaping detection (a false negative result). This probability is usually chosen to be 5%.

Detection threshold (DT): The instrument signal level used to determine if a measurement is IFB or not based on Fermilab measurement protocols. The detection threshold used at Fermilab in terms of detection signal is the critical level at 99% confidence level for the surface survey method (or equivalent to the detection limit at 95% confidence level for field or laboratory gamma spectrometry). The detection threshold used at Fermilab when converted to specific activity in an object is equivalent to the critical concentration for the surface survey method (or equivalent to the minimum detectable activity or concentration, MDA or MDC, for field or laboratory gamma spectrometry).

Evaluation of Potential Induced Radioactivity: The determination of the credible potential for residual volumetric contamination or activation through the consideration of process knowledge about the facility.

Impacted area: Areas at an accelerator site (normally within accelerator tunnels or radiological areas) where there is a reasonable potential for materials within the area to become activated or contaminated with radioactivity above background levels. Areas include any accelerator enclosures, equipment with activated air or water, and radioactive material outside of those areas.

Indistinguishable from background (IFB): The absence of detectable radioactivity as determined by evaluation or measurements.

Materials and equipment (M&E): A generic term for personal property that includes materials, equipment, apparatus, components, articles, etc. to which this document applies.

Measurement method: A set of processes and rules for making appropriate radiological measurements of potential volumetric radioactivity or surface activity for material release. The method includes the types of instruments and the measurement techniques. The measurement method for volumetric radioactivity in this document includes surface surveys and confirmatory measurements as warranted.

Measurement quality objective: A statement of a performance objective or requirement for a particular measurement method performance characteristic.

Non-impacted area: Areas at an accelerator site where there is no reasonable potential for materials present in the area to become activated or contaminated with radioactivity above background.

Personal property (or property): Property of any kind, except for real property [adapted from DOE Order 458.1 definition].

Process knowledge: A collective, objective description of the physical, operational, administrative, and radiological conditions associated with material being considered for clearance such that a reasonable and defensible decision can be made regarding whether the material could or could not have become activated or contaminated. Examples of process knowledge include, but are not limited to: the size, geometry, composition, and physical properties of the item; physics of radionuclide production in a facility; beam parameter and beam loss information, which allows for the evaluation of induced radioactivity; potential radioactivity distribution; and radiological measurement results.

Proxy radionuclide: An easy-to-measure radionuclide that may be used to infer the existence, activity, or dose of a hard-to-measure radionuclide, based on the established relationship between the two radionuclides.

Radiological Area: Any area within a Controlled Area defined as a Radiation Area, High Radiation Area, Very High Radiation Area, Contamination Area, High Contamination Area, or Airborne Radioactivity Area (see Articles 234, 235, 236, and Chapter 3 Part 3 of the FRCM).

Radiologically posted area: Any area that is posted for purposes of radiological protection, including Controlled Areas, Radioactive Material Areas, Radiological Buffer Areas, and Radiological Areas.

Real property: Land and anything permanently affixed to the land, such as buildings, fences, and those things attached to the buildings (such as light fixtures, plumbing and heating fixtures, or other such items) that would be personal property if not attached [adapted from DOE Order 458.1 definition].

Residual Radioactivity: Radioactivity that is above background levels due to: 1) technical enhancement of its concentration and/or 2) addition of radioactivity above background due to either radioactivation and/or cross contamination from facility operations.

Restricted Release: A subset of release defined as a reduction in the level of radiological control, or transfer of control to another party, where restrictions are placed on how the released items will be used or transferred.

Screening level (SL): Activity concentration (for either surface or volume radioactivity) that is designed to determine compliance with the primary dose criterion through comparison with radiation survey

results [adapted from ANSI N13.12-2013 definition]. The primary dose criterion is a total effective dose of 1 mrem/year, above background, for clearance of materials from regulatory control.

Site: A land or property upon which DOE facilities or activities are located and access to which is subject to DOE or DOE contractor control [adapted from DOE Order 458.1 definition].

Special Tritium Compound (STC): Any compound, except for H_2O, that contains tritium, either intentionally (e.g., by synthesis) or inadvertently (e.g., by contamination mechanisms). Also referred to as tritiated material.

Surface activity: Radioactivity residing on or near the surface of an item. This activity can be adequately quantified in units of radioactivity per unit surface area.

Surface surveys (for volumetric radioactivity): Measurements over the surfaces of an object to determine the presence or quantity of potential volumetric radioactivity within the object due to activation. The measurements may be conducted using a portable survey meter in a scanning and fixed-position measurement mode or using a gamma spectrometer in a fixed-position mode. This may be different from measurements for surface radioactivity.

Unrestricted Release: The removal of radiological regulatory controls from materials and equipment.

Volumetric radioactivity: Radioactivity residing in and throughout the volume of an item. At accelerator facilities, volumetric radioactivity in a material can result from volumetric activation by primary beam or secondary particles.

5.0 Material Release Program

5.1 Documentation System and Approach

This document facilitates implementation of requirements in DOE-STD-6004-2016 for the radiological clearance and release of personal property. The release criterion based on measurement protocols is that the instrument response or signal is indistinguishable from background (IFB). Establishing IFB via volumetric measurement protocols is accomplished at Fermilab using practical and sensitive field survey instruments with acceptable detection thresholds (DTs) and, as a best management practice, supplemented by confirmatory measurements. Confirmatory measurements can include field gamma spectrometry, radiochemical laboratory analysis of representative samples collected from the objects to be released, and the use of portal gate monitors.

Fermilab measurement instruments and methods have sufficiently low detection thresholds to satisfy the relevant regulatory requirements and standard recommendations. The Fermilab surface measurement protocol for potential volumetric radioactivity has detection thresholds that are lower than the ANSI N13.12 screening levels (SLs). The confirmatory measurements have DTs comparable to or lower than those of field survey methods.

Note that clearance is the unrestricted release of property that contains or may contain residual radioactive material from radiological control. Fermilab is <u>not</u> releasing or proposing to release any M&E that has detectable radioactivity above background. If Fermilab intends to release material other than that which is IFB, approval will be requested from the DOE Fermi Site Office (FSO) for the site's material release program, as required by DOE [DOE 2016].

This document includes the clearance protocols and the technical basis that can be used to justify and support unrestricted release of personal property. The clearance protocols in this document include three elements: (1) clearance criteria, (2) process knowledge, and (3) measurement methods.

Fermilab has established a Radiation Protection Program (RPP) and an Environmental Radiation Protection Program (ERPP), documented in the *Fermilab Radiological Control Manual* (FRCM) and supported by a comprehensive set of procedures, as required by 10 CFR 835, *Occupational Radiation Protection* and DOE Order 458.1, *Radiation Protection of the Public and the Environment*. Following the relevant regulations and standards, this document has been developed specifically for the Fermilab material release program (see Table 5.1), covering routine activities and larger decommissioning projects as part of a sound management system that satisfies DOE regulations and is consistent with best management practices in the accelerator community (see Table 5.2).

Table 5.1 *Documentation hierarchy for the Fermilab material release program*

Driver	Document Citation and Title	Compliance Type
DOE regulatory compliance	[DOE 2009] Title 10, Code of Federal Regulations, Part 835, *Occupational Radiation Protection* [DOE 1993] *Radiation Protection of the Public and the Environment*, DOE Order 5400.5, Chg 2 [DOE 2020] *Radiation Protection of the Public and the Environment*, DOE Order 458.1, Chg 4 [DOE 2016] *Clearance and Release of Personal Property from Accelerator Facilities*, DOE Standard 6004	Regulation
Fermilab policy implementation	Radiation Protection Program (RPP) Environmental Radiation Protection Program (ERPP) *Radiological Release and Clearance of Materials and Equipment,* ESH-RP-ERPP-01 *Surveys for Release and Clearance of Materials and Equipment from Radiological Control,* ESH-RPO-MON-09	Fermilab
Technical basis	*Technical Basis for Release of Materials from Radiological Control,* ESH-RP-ERPP-02	Fermilab
Supplemental regulatory information	[MARS 2002] *Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM)*, Report NUREG-1575, Rev. 1 [MARS 2009] *Multi-Agency Radiation Survey and Assessment of Materials and Equipment Manual (MARSAME)*, NRC Report NUREG-1575, Supp. 1	Optional guidance

Supplemental technical information	[IAEA 1996] *Clearance Levels for Radionuclides in Solid Materials*, IAEA-TECDOC-855 [ANSI 2013] *Surface and Volume Radioactivity Standards for Clearance*, ANSI N13.12 [EC 1998] *Recommended Radiological Protection Criteria for the Recycling of Metals from the Dismantling of Nuclear Installations*, EC Radiation Protection 89 [EC 2000] *Practical Use of the Concepts of Clearance and Exemption – Part I, Guidance on General Clearance Levels for Practices*, Radiation Protection 122 [NCRP 2002] *Managing Potentially Radioactive Scrap Metal*, NCRP Report No. 144 [ANS 2008] *Clearance of Solid Materials from Nuclear Facilities,* ANS Position Statement	Optional guidance

Table 5.2 *Material release process for routine activities and large facility-specific projects*

Project Type	**Process**
Routine activities that release small amounts of material	• May take a few days up to a few weeks to complete the release • Use of this technical basis document and RPP procedures • RSO approval • Reporting in the Annual Site Environmental Report (ASER)
Large facility-specific projects that release large amounts of material (e.g., from a non-operating facility or from a major facility upgrade)	• The project may be executed in phases and can take a few months up to a few years to complete the full release • Responsibility: line management defines the reuse or disposal options and provides process knowledge, such as historical beam losses to allow for the evaluation of potential induced activity • Inventory/tracking: tracking system recommended for large scale material release projects to archive the records of process knowledge, item inventory, survey results, on-site reuse or storage, and off-site disposal and release • Approval by line management and the RSO • Reporting in the Annual Site Environmental Report (ASER)

5.2 Process Flow for Fermilab Material Management and Unrestricted Release

Figures 5.1 and 5.2 illustrate the general process that Fermilab utilizes to carry out unrestricted releases. Line management and Fermilab divisions and sections, such as the ES&H Section and the Facilities Engineering Services Section (FESS), have important roles and responsibilities in implementing the material release program.

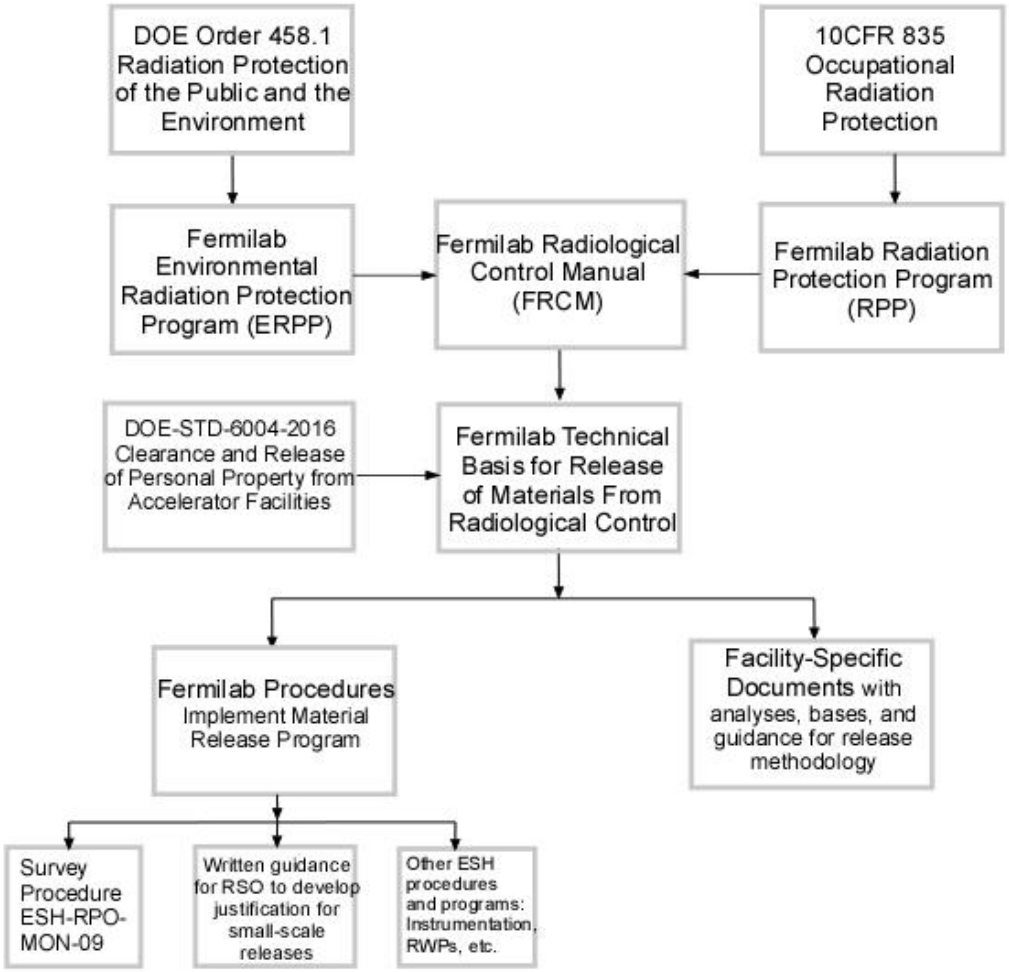

Figure 5.1 *Hierarchy of documents pertaining to Fermilab's material release program*

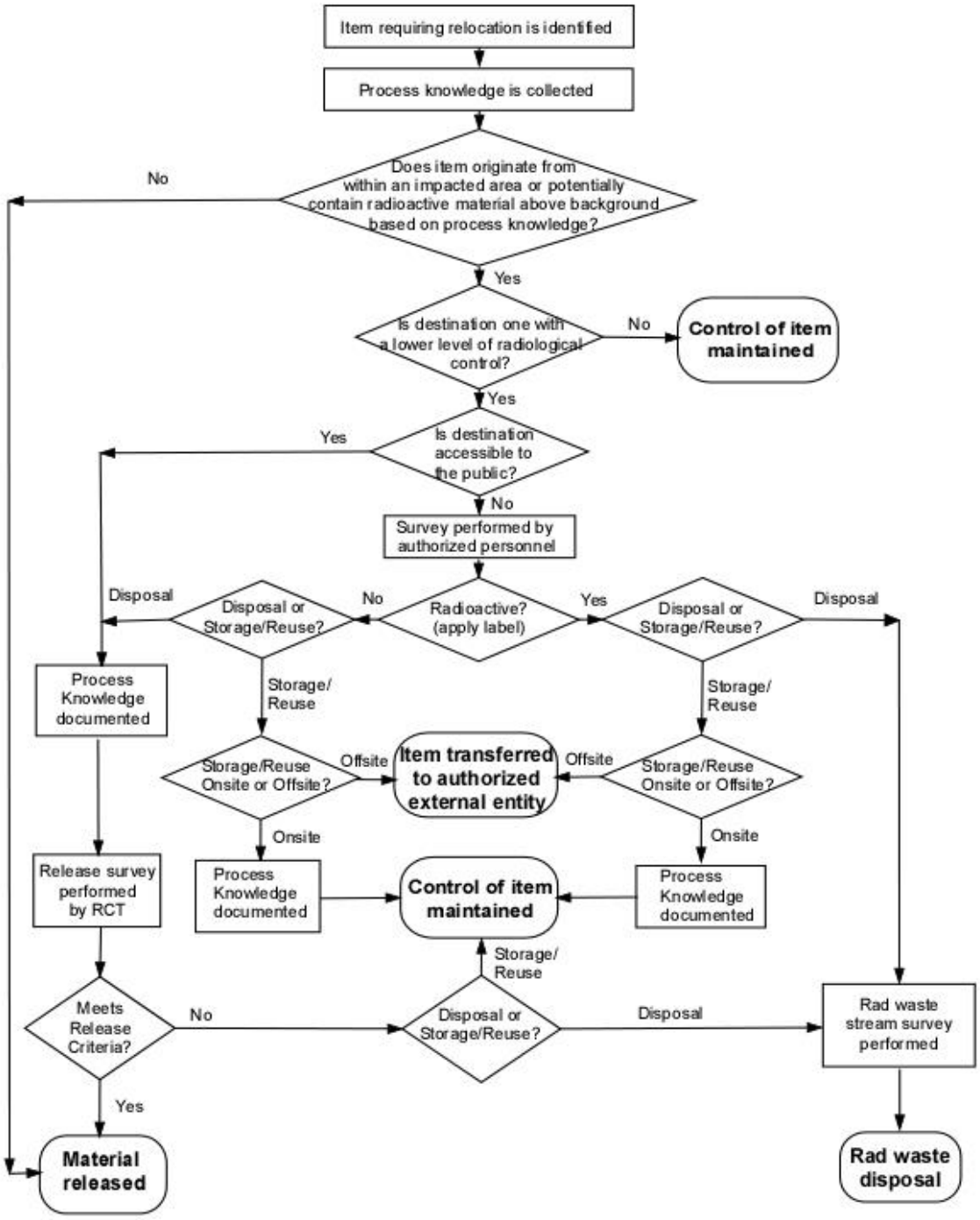

Figure 5.2 *Overview of Fermilab material release process*

Large facility upgrade or dismantling projects which involve the release of significant amounts of M&E require an effective process flow. The project needs integration and coordination among different parties involved (including subcontractors) to address all types of issues (administrative, operational, technical, etc.) and hazards (radiological, chemical, industrial, environmental, etc.) associated with the project.

For large projects, Fermilab deactivation and decommissioning (D&D) documents are developed by the key parties involved to describe a project's scope, responsibilities, tasks, and process knowledge. For example, radioactive material identification and dose rate estimates are conducted for disassembly of beam interaction points, such as for a Neutrinos at the Main Injector (NuMI) horn shown in Figure 5.3.

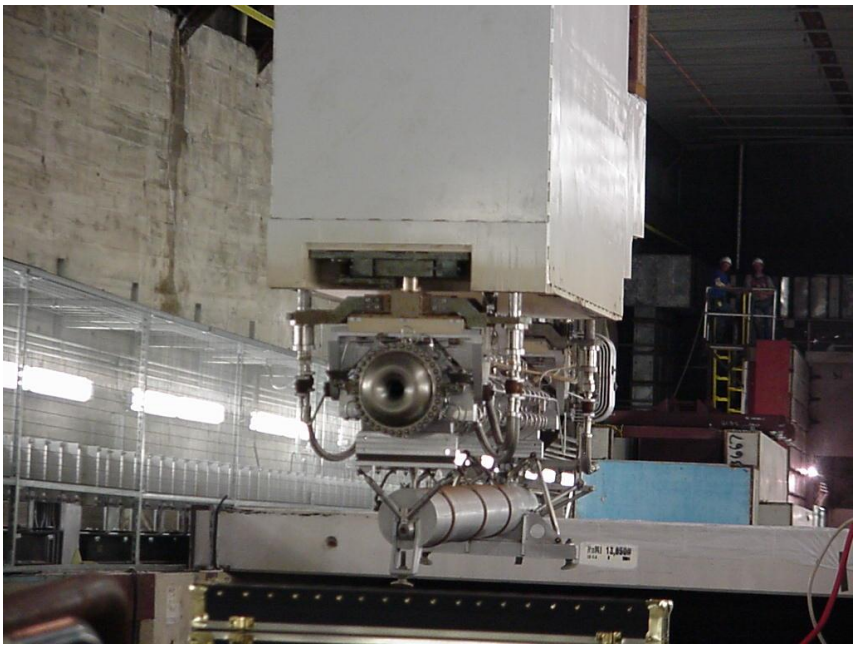

Figure 5.3 *NuMI horn replacement*

The ERPP material management program consists of radioactive material identification, survey, and control to ensure proper storage, use, and release by utilizing the following implementation requirements:

1. All items which were located inside of accelerator or beamline enclosures during beam operations are considered potentially radioactive and are classified as impacted material.
2. Authorized personnel conduct radiological surveys to characterize material per FRCM Chapter 4 and procedure ESH-RPO-MON-09, *Surveys for Release and Clearance of Materials and Equipment from Radiological Control.*
3. If M&E is surveyed and determined to be radioactive, then the M&E is subject to radiological control.

The Fermilab material release program is also integrated as an element of the RPP, particularly related to the area management, material management, and instrumentation programs. The RPP area management program consists of area classification, area posting, and area survey to ensure that potentially radioactive materials are properly managed and controlled within designated areas at Fermilab. The program has the following process:

1. All accelerator or beamline tunnels (e.g., Linac, Booster, 8 GeV, Main Injector, Switchyard, Delivery Ring) are equipped with interlocked access control systems to protect people from exposure to prompt radiation during beam operation.
2. Entrances to, and specific locations inside, the enclosures in which accelerators or beam lines can produce potential induced radioactivity are posted as Controlled Areas, Radioactive Material Areas, Radiological Buffer Areas, or Radiological Areas to control personnel exposure to residual radioactivity.
3. A few limited locations which have potential for surface contamination are posted as Contamination Areas and are monitored and controlled per Radiation Physics procedures.
4. Radiation Physics Operations (RPO) regularly surveys the Radiological Areas and maintains an updated status list of Radiological Areas due to the existence of induced radioactivity.
5. Radiological Work Permits (RWPs) are used to control the work in Radiological Areas.
6. Lab-wide material survey protocols have been established to manage the removal of M&E from various radiologically posted areas.
7. All area posting/survey/control processes above are also applicable to facilities that are no longer operational or active.

The ES&H Section Radiation Physics Calibration Facility (RPCF) maintains the instrumentation and provides technical support for conducting radiological surveys. Instruments used for material release measurements are properly chosen for their sensitivity to the radionuclides of interest and calibrated using traceable standards at least annually when in-use. They are also response-checked by users at least daily prior to use and are operated by trained and qualified individuals only.

5.3 Material Release Protocol

The material release protocols at Fermilab include the following three elements:

1. Release criterion approved by DOE (section 5.3.1),
2. Process knowledge (section 5.3.2), and
3. Measurement methods for surface and volumetric radioactivity (section 5.3.3)

Process knowledge may be used to identify the areas, conditions, and operations that can potentially contaminate or activate materials. When process knowledge itself is not sufficient to establish the clearance decision, materials shall be measured with appropriate instruments and techniques for surface or volumetric radioactivity to determine if the selected clearance criteria are met and materials may be released.

5.3.1 Release criterion

5.3.1.1 Surface Radioactivity

DOE Order 458.1 allows the use of previously approved guidelines or limits as the pre-approved Authorized Limits for unrestricted release of personal property that may potentially be surface contaminated. The surface contamination guidelines given in DOE Order 5400.5 Figure IV-1 are considered previously approved authorized limits [DOE 2016]. Property may be released if the results of a survey with appropriate instruments indicate that the potential activity of the property is less than the surface contamination guidelines given in DOE Order 5400.5 Figure IV-1.

DOE Order 5400.5 Figure IV-1 does not have surface contamination guidelines for tritium. Appendix D to 10 CFR 835 sets a removable surface contamination value of 10,000 dpm/100 cm^2 for tritium, which DOE guidance recommends as an acceptable limit for unrestricted release [DOE 1991]. Typically, tritium permeates the volume of whatever material is contaminated, so no value is given for total contamination (fixed + removable). Measurements demonstrating compliance of the removable fraction of tritium on surfaces with this guideline are acceptable to ensure nonremovable fractions and residual tritium in mass will not cause exposures that exceed DOE dose limits and constraints [DOE 2002]. The total residual surface activity guidelines from DOE Order 5400.5 Figure IV-1 (and 10 CFR 835 for tritium and STCs) are summarized below in Table 5.3 [DOE 2002].

Table 5.3 *Allowable Total Residual Surface Activity (dpm/100 cm^2) [a, b]*

Radionuclides[c]	Average[d,e]	Maximum[d,e]	Removable[f]
Group 1—Transuranics, ^{125}I, ^{129}I, ^{227}Ac, ^{226}Ra, ^{228}Ra, ^{228}Th, ^{230}Th, ^{231}Pa	100	300	20
Group 2—Th-natural, ^{90}Sr, ^{126}I, ^{131}I, ^{133}I,^{223}Ra, ^{224}Ra, ^{232}U, ^{232}Th	1,000	3,000	200
Group 3—U-natural, ^{235}U, ^{238}U, associated decay products, alpha emitters	5,000	15,000	1,000
Group 4—Beta-gamma emitters (radionuclides with decay modes other than alpha emission or spontaneous fission) except ^{90}Sr and others noted above[g]	5,000	15,000	1,000
Tritium and STCs (applicable to surface and subsurface)[h]	N/A	N/A	10,000

[a] The values in this table (except for tritium) apply to radioactive material deposited on but not incorporated into the interior or matrix of the property. Authorized limits for residual radioactive material in volume must be approved separately.

[b] As used in this table, dpm (disintegrations per minute) means the rate of emission by radioactive material as determined by counts per minute measured by an appropriate detector for background, efficiency, and geometric factors associated with the instrumentation.

[c] Where surface contamination by both alpha-emitting and beta-gamma-emitting radionuclides exists, the limits established for alpha-emitting and beta-gamma-emitting radionuclides should apply independently.

[d] Measurements of average contamination should not be averaged over an area of more than 1 m^2. Where scanning surveys are not sufficient to detect levels in the table, static counting must be used to measure surface activity. Representative sampling (static counts on the areas) may be used to demonstrate by analyses of the static counting data. The maximum contamination level applies to an area of not more than 100 cm^2.

[e] The average and maximum dose rates associated with surface contamination resulting from beta-gamma emitters should not exceed 0.2 millirad per hour (mrad/h) and 1.0 mrad/h, respectively, at 1 cm.

[f] The amount of removable material per 100 cm^2 of surface area should be determined by wiping an area of that size with dry filter or soft absorbent paper, applying moderate pressure, and measuring the amount of radioactive material on the wiping with an appropriate instrument of known efficiency. When removable contamination of objects on surfaces of less than 100 cm^2 is determined, the activity per unit area should be based on the actual area, and the entire surface should be wiped. It is not necessary to use wiping techniques to measure removable contamination levels if direct scan surveys indicate the total residual surface contamination levels are within the limits for removable contamination.

[g] This category of radionuclides includes mixed fission products, including the ^{90}Sr that is present in them. It does not apply to ^{90}Sr that has been separated from the other fission products or mixtures where the ^{90}Sr has been enriched.

[h] Measurement should be conducted by a standard smear measurement but using a damp swipe or material that will readily absorb tritium, such as polystyrene foam. Property recently exposed or decontaminated should have measurements (smears) at regular time intervals to prevent a buildup of contamination over time. Because tritium typically penetrates material it contacts, the surface guidelines in group 4 do not apply to tritium. Measurements demonstrating compliance of the removable fraction of tritium on surfaces with this guideline are acceptable to ensure nonremovable fractions and residual tritium in mass will not cause exposures that exceed DOE dose limits and constraints.

5.3.1.2 Volumetric Radioactivity

Based on a dose constraint of 1 mrem/yr to the public, the ANSI N13.12-2013 Standard, *Surface and Volume Radioactivity Standards for Clearance,* establishes the screening levels (SLs) for the clearance of personal property with potential surface or volumetric radioactivity. For volumetric radioactivity, the ANSI N13.12-2013 volume SLs are expressed in radioactivity per unit mass for residual radionuclides within a material, separated into five groups (see Table 5.4).

Table 5.4 *ANSI N13.12-2013 SLs for volumetric activity*

Radionuclide Groups[1]	**Volume SLs (pCi/g)**
Group 1: High-energy gamma, radium, thorium, transuranics, and mobile beta gamma emitters (e.g., ^{22}Na, ^{54}Mn, ^{60}Co, ^{65}Zn, and ^{152}Eu)	3
Group 2: Uranium and selected beta-gamma emitters (e.g., ^{57}Co, ^{58}Co, and ^{59}Fe)	30
Group 3: General beta-gamma emitters (e.g., ^{7}Be)	300
Group 4: Low-energy beta-gamma emitters (e.g., ^{3}H and ^{63}Ni)	3,000
Group 5: Low-energy beta emitters (e.g., ^{55}Fe)	30,000

[1]ANSI N13.12-2013 provides a more complete list of radionuclides

DOE-STD-6004-2016 prescribes 3-tiered clearance criteria related to ANSI N13.12-2013 volume SLs that may be used by DOE sites:

1. A criterion of indistinguishable from background (IFB) at a level lower than the SLs,
2. A criterion equal to the SLs, and
3. A criterion higher than the SLs.

Fermilab has chosen the IFB clearance criterion. The IFB criterion is consistent with O 458.1 paragraph 4.k.(3)(a) in releasing property not containing residual radioactive material. The IFB clearance criterion is applied to property that is expected to have no residual volumetric radioactivity. This expectation is confirmed by clearance measurements with results that are indistinguishable from ambient background radiation levels.

The IFB level of a measurement method depends on the detection capability. Different measurement methods in different background levels can have different IFB levels. Therefore, the measurement methods must have sufficient detection capability (which is less than the ANSI N13.12-2013 volume SLs) to provide reasonable assurance that material released based on this criterion satisfy the 1 mrem/yr dose constraint in O 458.1.

The measurement methods described in Section 5.3.3 and Appendix A of this document are designed to meet these objectives. Release with IFB clearance criterion requires only that radioactivity is *not detectable*, using appropriate instruments and techniques, and does not specifically invoke a quantitative radioactivity determination. In this case, detection thresholds (DTs), defined in Appendix B, for proxy radionuclides shall be less than the ANSI N13.12-2013 volume SLs.

Unless approval is obtained from the FSO to release material using criteria other than IFB, materials exceeding IFB can only be reused on-site, transferred to another DOE facility, transferred to a facility or individual licensed and authorized to possess the radioactivity, or disposed of as radioactive waste. Radioactive waste is processed and disposed of by the ES&H Section Hazard Control Technology Team (HCTT).

5.3.2 Process Knowledge

Process knowledge is routinely collected by workers when materials are to be relocated. When necessary, process knowledge is documented using Fermilab's Material Move Request (MMR) process and the restricted release process and includes the evaluation of facility records for operations or activities that could potentially contaminate or activate materials. The process knowledge that provides the information necessary for evaluation of potential induced radioactivity includes:

- Physics of radionuclide production (activation and radioactive decay and progeny ingrowth, types and yields of radionuclides that can be produced as a function of radiation particle type and energy, radioactivity distribution, etc.)
- Accelerator and beam characteristics (e.g., accelerator and beamline layout, beam particle type, beam energy, beam loss locations and amounts, etc.)
- Material and component characteristics (e.g., type, size, geometry, composition and physical property of material and components, as well as common impurities)
- Accelerator and facility operations (e.g., the period and length of beam-on operations, the cool-down time or decay time, the maintenance/repair activities that may cause surface contamination, etc.)

If process knowledge cannot demonstrate that property does not contain residual radioactivity, radiological measurements (described in section 5.3.3) shall be conducted to supplement process knowledge evaluations.

If there is sufficient process knowledge to establish that materials have no potential for either surface or volumetric radioactivity, the materials may be released without subjecting them to the release process, including the measurement methods. If not supplemented by radiological measurements, process knowledge evaluations shall be adequate to determine: (1) whether the property has ever been used for radiological activities or in areas that could have resulted in the presence of residual radioactive material within or on the property, or (2) whether property formerly containing residual radioactive material has been decontaminated and demonstrated to meet the O 458.1 Authorized Limits and has not been used in a manner or in areas that could have resulted in the re-contamination of the property.

General process knowledge for volumetric activation in most accelerator facilities is listed below [DOE 2016, SLAC 2011b]. These results, though qualitative, serve as one type of process knowledge which helps define the areas and activities that can potentially contaminate property.

1. Klystrons operated at < 1 MeV do not cause activation and, if they are not located inside any accelerator tunnel, they will not be activated either. Though the immediate area surrounding a klystron is generally posted conservatively as a radiation area when the klystron is on for the purpose of personnel exposure control for prompt radiation, they generally do not induce radioactivity.
2. Low-energy x-ray devices do not have activation potential.
3. High energy electron accelerators have low activation potential. For example, on an equal beam power loss basis, electron accelerators have activation potential that is a factor of ~100 lower than proton accelerators.
4. The higher the beam energy (when exceeding the activation thresholds of the materials), the higher the beam loss, or the longer the beam loss period, the higher the activation.
5. Large experimental detector regions (except near the target or collision point) are expected to have lower activation potential than regions with accelerators or electron beam lines, because the beam losses near a detector must be very small, if not zero, to avoid detector background interference problems.
6. Storage ring accelerators have lower activation potential than linear accelerators due to their lower integral beam losses. Figure 5.4 displays the g-2 experiment storage ring, and a section of typical components present in an accelerator tunnel at the Muon Campus.

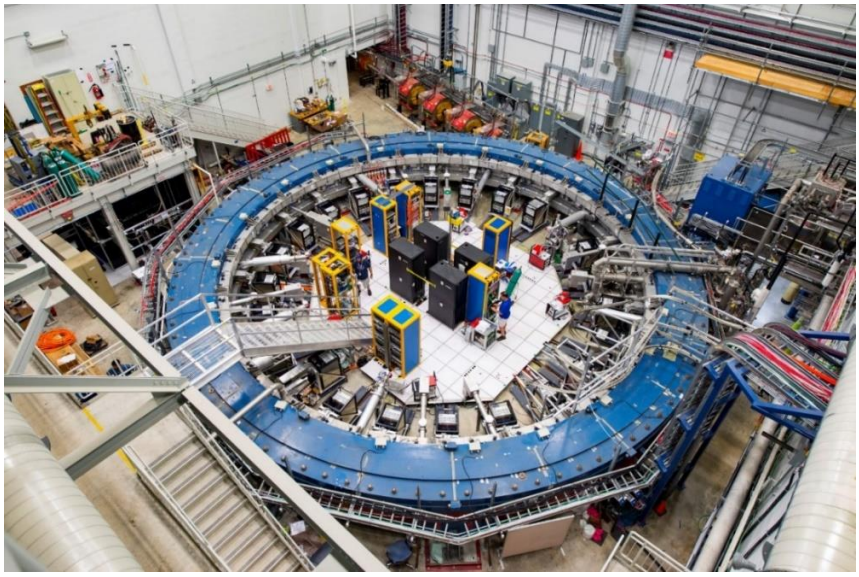

Figure 5.4 *Fermilab g-2 muon storage ring at the MC-1 Service Building*

7. Areas with potential activation are within the accelerator enclosure, where access is prohibited by an interlocked access control system to prevent personnel exposure to prompt radiation coming from accelerator beam losses.

8. The potential for activation inside the accelerator enclosure is highest in locations near normal beam loss points, such as beam targets, beam absorbers, collimators, and slits (these components are designed to intercept a fraction of or the entire beam).

5.3.2.1 Electron Accelerator Facilities

At Fermilab's FAST facility, electrons are accelerated through an electron injector to an energy of 150 MeV. Common metals in the accelerator structure include aluminum, iron, copper, and steel, with the main elements present in steel being iron and nickel. Accelerator enclosure walls and floors are almost always made of concrete (mainly SiO_2).

Appendix C of DOE-STD-6004 describes the technical basis for the material clearance at high-energy electron accelerator facilities, supported by benchmark experiments and FLUKA evaluations conducted by SLAC National Accelerator Laboratory [SLAC 2011b]. SLAC is an electron accelerator laboratory providing an electron beam up to 15 GeV. Their calculations using FLUKA to evaluate the induced radioactivity levels in various components based on estimated beam losses have been conducted for many projects, all with the same materials found at the FAST facility and at energies higher than those produced at the FAST facility. Therefore, the process knowledge outlined in DOE-STD-6004 that summarizes the characteristics of the induced radionuclides and volumetric radioactivity in materials due to activation may be used [DOE 2016].

The most abundant radionuclides that can be produced from activation in these materials are those with a half-life on the order of the typical irradiation time, a few months to a few years [DOE 2016]. Table 5.5 summarizes the radionuclides with a half-life longer than 200 days and shorter than 100 years that can be produced in common accelerator materials [SLAC 2011b]. The radionuclides where the production yield is the highest for each element have been indicated with "main."

Table 5.5 *Radionuclides that can be produced in common accelerator materials*

Radionuclide	Half-life	Decay Modes	O	Al	Si	Fe	Ni	Cu
^{3}H	12.3 yr	β^-, no ɣ	main	✓	✓	✓	✓	✓
^{22}Na	2.6 yr	β^+, ɣ		main	main	✓	✓	✓
^{54}Mn	312 d	ε, ɣ				main	✓	✓
^{55}Fe	2.73 yr	ε, x, no ɣ				main	✓	✓
^{57}Co	272 d	ε, ɣ				main	main	✓
^{60}Co	5.26 yr	β^-, ɣ					main	main
^{63}Ni	100 yr	β^-, no ɣ						main

Most induced radionuclides are beta-gamma emitters, while no alpha emitters and very few pure beta emitters are produced. A few radionuclides are difficult to measure because they emit only betas (e.g., ^{3}H and ^{63}Ni) or low energy x-rays (e.g., 5.9 keV x-ray from ^{55}Fe). However, these hard-to-measure radionuclides always occur in the presence of other radionuclides that emit high-energy and high-yield gamma rays, which are easy to measure with common instruments [SLAC 2011b].

These easy-to-measure radionuclides are called “proxy” radionuclides because measurements of these radionuclides can be used to infer the radioactivity levels of the hard-to-measure radionuclides. Table 5.6 summarizes the main radionuclides and proxy radionuclides that can be produced in stainless steel, copper, iron, aluminum, and concrete [SLAC 2011b].

The important proxy radionuclides in metal are ^{22}Na, ^{54}Mn, and ^{60}Co. In concrete, radionuclides ^{152}Eu and ^{60}Co, whose radioactivity level depends strongly on thermal neutron fluence and the trace amounts of europium and cobalt nuclides (which have very large thermal neutron cross sections), can be measured in most concrete samples and thus can also serve as proxy radionuclides.

Of special concern is the production and detection of ^{3}H, which is not detected by gamma survey, but which generally scales with that of the proxy radionuclides. Only in the case of activated concrete which has aged for many years after exposure is there significant likelihood of the presence of ^{3}H above background levels in the absence of detectable proxy radionuclides. Process knowledge should be used to support release decisions for concrete, and where this process knowledge is not robust, additional sampling and analysis may be required.

It is not coincidental that proxy radionuclides belong to the ANSI N13.12-2013 Group 1 radionuclides while the hard-to-measure radionuclides belong to the ANSI N13.12-2013 Group 4 or Group 5 radionuclides. This is because proxy radionuclides emit high-yield and high-energy gammas such that they dominate the dose rate on the item’s surface and simultaneously create higher dose risk.

To satisfy the release criterion of IFB, no radioactivity must be detected. Therefore, the “Sum of Fractions” of the DT to the corresponding SL value for all radionuclides of concern should be ≤ 1 [SLAC 2011b]. Thus, the Fermilab DT requirement for IFB release is expressed as follows:

$$\sum_i \left(\frac{\mathrm{DT}_i}{\mathrm{SL}_i}\right) \leq 1$$

where:

i = Radionuclide *i* of concern (including both proxy and hard-to-measure radionuclides)
DT_i = detection threshold for radionuclide *i* in pCi/g
SL_i = ANSI N13.12 Screening Level for radionuclide *i* in pCi/g

The characteristic of proxy radionuclides is essential and important for clearance measurements: if the proxy radionuclides are not detected (i.e., measurements are IFB), the hard-to-measure radionuclides will not be present at a level that would create a radiation risk either. Therefore, measurements of proxy radionuclides are sufficient to characterize the materials for release.

Table 5.6 *Main and proxy radionuclides in metal and concrete materials*

Material	Radionuclide	Half-Life	Main Production	Major ɣ Energy	Proxies, Remarks
Carbon steel (Fe, C), Cast iron (Fe, C, Si, Mn)	^{22}Na	2.6 yr	Fe, Si, Mn spallation	1.27 MeV (100%)	
	^{54}Mn	312 d	^{55}Mn (ɣ,n)	835 keV (100%)	
	^{55}Fe	2.73 yr	^{56}Fe (ɣ,n)	5.9 keV x-ray	^{22}Na
	^{57}Co	272 d	^{58}Fe (p,2n)	122 keV (86%) 133 keV (10%)	
Austenitic stainless steel (Fe, C, Cr, Ni) & Copper	The same radionuclides as carbon steel and cast iron, plus:				
	^{60}Co	5.26 yr	^{60}Ni (n,p), Cu spallation	1.17 MeV (100%) 1.33 MeV (100%)	
	^{63}Ni	100 yr	^{64}Ni (ɣ,n), Cu spallation	no ɣ	^{60}Co
Superaustenitic, Ferritic, Martensitic SS (Fe, C, Cr, Ni, Mo)	The same radionuclides as austenitic SS and copper, plus:				
	^{93m}Nb	16.3 yr	Mo spallation	31 keV x-ray	^{60}Co
	^{90}Sr	28.8 yr	Mo spallation	no ɣ	^{60}Co
	^{85}Kr	10.8 yr	Mo spallation	514 keV (0.4%)	^{60}Co
	^{65}Zn	244 d	Mo spallation	1116 keV (51%)	
Aluminum	^{22}Na	2.6 yr	Al spallation	1.27 MeV (100%)	
Concrete (trace amounts of Eu and Co, with large thermal neutron cross sections)	^{3}H	12.3 yr	O, Si spallation	no ɣ	^{22}Na, ^{60}Co, ^{152}Eu
	^{22}Na	2.6 yr	Si spallation	1.27 MeV (100%)	
	^{54}Mn	312 d	^{55}Mn (ɣ,n)	835 keV (100%)	
	^{55}Fe	2.73 yr	^{56}Fe (ɣ,n)	5.9 keV x-ray	^{22}Na
	^{57}Co	272 d	^{58}Fe (p,2n)	122 keV (86%) 133 keV (10%)	
	^{60}Co	5.26 yr	^{59}Co (n,ɣ)	1.17 MeV (100%) 1.33 MeV (100%)	Thermal Neutron Capture
	^{152}Eu	13.5 yr	^{151}Eu (n,ɣ)	many (sum > 140%)	
	^{154}Eu	8.59 yr	^{153}Eu (n,ɣ)	many (sum > 150%)	

5.3.2.2 Proton Accelerator Facilities

Many characteristics of volumetric activation at proton accelerators that are relevant to material release are the same as those for electron accelerators. The reason for this similarity is because the dominant reactions producing the induced radionuclides of interest are the same for electron and proton accelerators. This is true particularly for proton beam energies higher than 100 MeV, where spallation reactions become the dominant reaction for induced radioactivity production.

Like electron accelerators, common metals in proton accelerators are aluminum, iron, copper, and steel. Production mechanisms are chiefly identified by material types, their proximity to the actual proton beams, and the energy and power of the proton beam. As the target atomic number increases, so does the range of activation products.

Table 5.7 lists activation products that have half-lives between 30 days and 101 years in metals in a proton accelerator [DOE 2016]. Though the radionuclides in the table consider spallation, evaporation, and absorption products, the specific mix of radionuclides depends on both the energy of the proton beam and the distance to the metals being considered.

Table 5.7 *Common activation products in metals in proton accelerators*

Metal	**Induced Radionuclide**
Aluminum	^{7}Be, ^{45}Ca, ^{3}H, ^{22}Na
Iron, steel	As listed for aluminum, plus ^{56}Co, ^{57}Co, ^{58}Co, ^{60}Co, ^{55}Fe, ^{59}Fe, ^{54}Mn, ^{124}Sb, ^{125}Sb, ^{46}Sc, ^{113}Sn, ^{44}Ti, ^{88}Y, ^{88}Zr
Copper	As listed for iron and steel, plus ^{63}Ni, ^{65}Zn

The radionuclides emitting only betas or low-energy or low-yield photons (e.g., ^{3}H, ^{7}Be, ^{45}Ca, ^{55}Fe, and ^{63}Ni) are referred to as “hard to measure.” The residual radioactivity in material depends on the material type, activation type (directly activated by proton beam or activated by secondary particles, and at what energy), irradiation time, and decay time. In most cases, the radionuclides that are hard to measure are accompanied by proxy radionuclides that are reasonably easy to detect.

To estimate radionuclide concentrations in materials, extensive calculations were performed for proton beam loss events at energies from 17 MeV to 12 GeV for stainless steel, copper, and aluminum, along with varied irradiation times and decay times [DOE 2016]. Tables 5.8 – 5.10 summarize the calculated results for both distal (metals farther away from the proton beam, activated by secondary products) and proximal (metals directly exposed to a proton beam, activated by primary and secondary interactions) cases. The hard-to-measure radionuclides and the proxy radionuclide that may be used, along with limitations, are identified. The last column in each table identifies whether the hard-to-measure radionuclide is less than the ANSI SL value.

Table 5.8 *316 Stainless Steel*

	Energy	Hard-to-Measure Radionuclide	Proxy	Limitations	< SL?
Distal	17 MeV	^{55}Fe	^{58}Co	Strongly dependent on irradiation/decay times. ½ y irradiation: 50 y decay. 30 y irradiation: 5 y decay.	Always
	65 MeV – 12 GeV	^{55}Fe, ^{3}H	^{54}Mn	Up to 10-20 y decay	Decay times > 5 y
Proximal	17 MeV	^{55}Fe	^{54}Mn	Up to 10 y decay	Decay times > 40 y
	65 MeV	^{55}Fe, ^{3}H	^{54}Mn	Up to 15-20 y decay	
	400 MeV	^{55}Fe, ^{3}H	^{22}Na	Up to 20-30 y decay	
	12 GeV	^{55}Fe, ^{3}H	^{22}Na	Up to 25-30 y decay	

Table 5.9 *Copper*

	Energy	Hard-to-Measure Radionuclide	Proxy	Limitations	< SL?
Distal	17 MeV	^{63}Ni	^{60}Co	Up to 30-40 y decay	Always
	65 MeV – 12 GeV	^{63}Ni	^{60}Co	None	
Proximal	17 MeV	^{63}Ni	^{60}Co	Up to 30-40 y decay	Irradiation times < 10 y
	45 MeV	^{3}H, ^{63}Ni	^{60}Co	None	No
	400 MeV	^{3}H, ^{55}Fe, ^{63}Ni	^{60}Co	None	No
	12 GeV	^{3}H	^{60}Co	None	No

Table 5.10 *6061 Aluminum*

	Energy	Hard-to-Measure Radionuclide	Proxy	Limitations	< SL?
Distal	17 MeV	^{3}H	^{26}Al	None	Always
	65 MeV – 12 GeV	^{3}H	^{22}Na, ^{26}Al	None	
Proximal	17 MeV	^{55}Fe	^{54}Mn, ^{26}Al	None	> 20 y decay
	65 MeV	^{3}H	^{22}Na, ^{26}Al	None	> 30 y decay
	400 MeV	^{3}H	^{22}Na, ^{26}Al	None	> 50 y decay
	12 GeV	^{3}H, ^{7}Be	^{22}Na	Up to 20 y decay	> 50 y decay

Limitations on the use of the proxy radionuclide approach are based on their relative radioactivity, along with their relative hazard. Some limitations that may be drawn from Tables 5.8 – 5.10 include:

1. For 316 stainless steel, ^{55}Fe may be a problem for long decay times for most proton energies. Its long half-life and production mechanisms cause it to be the predominant radionuclide by far when other radionuclides may decay away after 10-20 years. For a distal case at a 17-MeV proton beam, ^{58}Co can serve as proxy.
2. For copper, the proxy for hard-to-measure radionuclides covers a wide range of irradiation and decay periods, in most cases for greater than 50 years decay.
3. For 6061 aluminum alloy, the proxies for ^{3}H cover a wide range of conditions. If pure aluminum is considered, the unusual case of ^{55}Fe as the only hard-to-measure radionuclide of concern in one case is no longer an issue.

Additional comprehensive calculations have been conducted for the induced radioactivity profiles in common beamline and shielding materials in several typical beam loss geometries for a proton beam from 160 MeV to TeV as a function of irradiation and decay time periods [CERN 2011]. The induced radioactivity profiles confirm the similarity between electron and proton accelerators. Tables 5.11 and 5.12 show the induced radioactivity profiles for steel shielding surrounding a 160-MeV proton beam absorber (made of graphite and stainless steel) after 30-year irradiation and a 2-year decay [DOE 2016]. The SL fraction is the ratio of the radioactivity to SL for each radionuclide.

Table 5.11 *Induced radioactivity for steel shielding surrounding a 160-MeV proton beam absorber after 30-year irradiation and 2-year decay*

Radionuclide	Half-Life	Volumetric Radioactivity (Bq/g)	ANSI SL (Bq/g)	SL Fraction
^{3}H	12.3 y	17	100	0.17
^{49}V	338 d	14	100	0.14
^{54}Mn	313 d	50	0.1	500
^{55}Fe	2.74 y	430	1,000	0.43
^{57}Co	272 d	10	1	10
^{60}Co	5.27 y	340	0.1	3400
^{63}Ni	100 y	14	100	0.14

Table 5.12 *Induced radioactivity profiles for steel and concrete shielding surrounding a 160-MeV proton beam absorber (graphite and stainless steel) after 30-year irradiation and 2-year decay*

Component	Absorber		Shielding	
Material	Graphite	Stainless Steel	Steel	Concrete
Radionuclide (Radioactivity in %)	^{3}H (100%)	^{55}Fe (76%)	^{55}Fe (49%)	^{3}H (75%)
		^{54}Mn (11%)	^{60}Co (39%)	^{55}Fe (11%)
Radionuclide (SL Fraction in %)	^{3}H (100%)	^{54}Mn (88%)	^{60}Co (87%)	^{22}Na (87%)
		^{60}Co (7%)	^{54}Mn (13%)	^{54}Mn (12%)

Tables 5.11 and 5.12 show that, for a steel absorber and steel shielding:

1. The radionuclides of interest and proxy radionuclides are the same as those in electron accelerators.
2. Proxy radionuclides (^{54}Mn and ^{60}Co in steel; ^{22}Na and ^{54}Mn in concrete) dominate the total dose risk (> 99%), when normalized to the corresponding ANSI SLs, while hard-to-measure radionuclides (^{3}H, ^{55}Fe and ^{63}Ni) are insignificant though they may have higher radioactivity.
3. One exception is the graphite absorber, which has only ^{3}H produced and no proxies can be used, due to graphite's low atomic number [DOE 2016].

As extensive calculations have been performed for activation products in stainless steel, copper and aluminum at proton beam energies ranging from 17 MeV to 1 TeV, Fermilab has accepted these quantities and ratios as the source term for these three materials, as both the materials and beam energies are comparable to those found in the Fermilab accelerator complex.

5.3.2.3 Induced radioactivity profiles at Fermilab

Additional materials found at the Fermilab accelerator complex that were not fully reviewed in DOE-STD-6004-2016 are carbon steel and high-density concrete. To determine the source term for carbon steel and high-density concrete, calculations were performed with MARS Monte Carlo code [MCNP 2018] to determine the radioactivity of proxy radionuclides and any hard-to-measure radionuclides, and their corresponding dose risks. The proximal calculations for carbon steel were for a beam pipe directly impacted by the proton beam, an end strike on a 1-meter long, 6-inch radius, 0.25-inch-thick volume located 1 meter downstream from the beam origin. The distal calculation for carbon steel was for the same beam pipe located 1.513 meters perpendicular to the beamline (see Figure 5.5). Concrete is not only the material used in accelerator walls and floors, but also the frequent choice for the construction of shielding walls. Therefore, the MARS simulation modeled a high-density concrete block measuring 1 m^3 located 1.513 meters perpendicular to the beamline for a distal case; for a proximal case, a 1 m^3 block with a 7.5 cm diameter central bore was located 1 meter downstream of the target (see Figure 5.6).

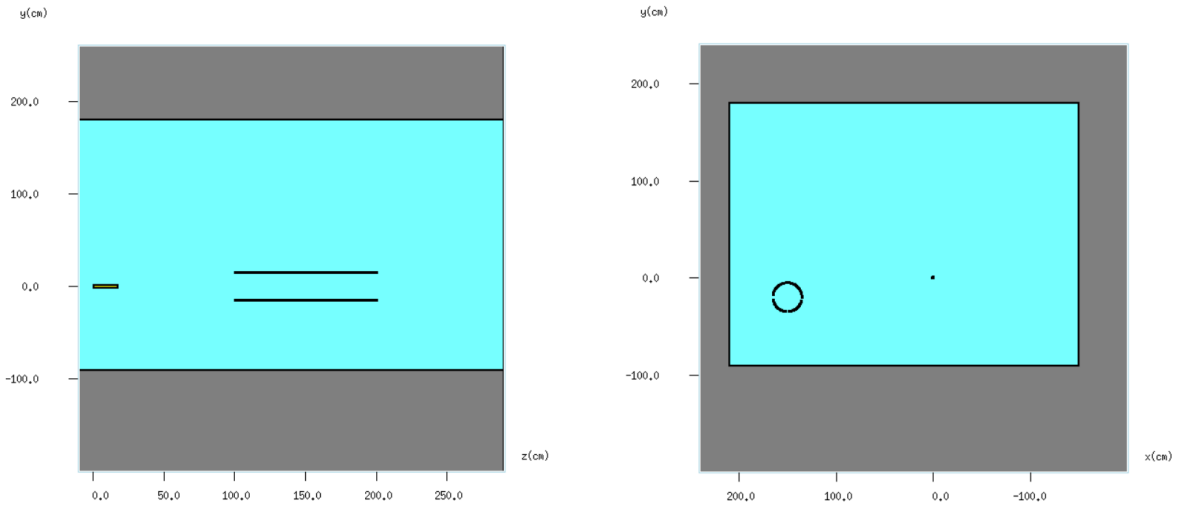

Figure 5.5 *MARS models for a carbon steel pipe for proximal (left) and distal (right) locations*

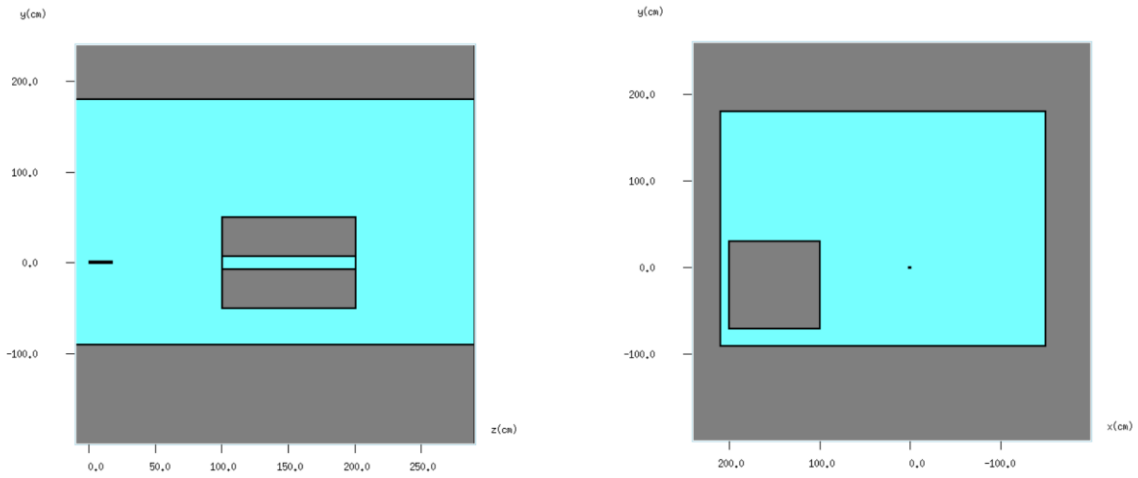

Figure 5.6 *MARS models for a concrete block for proximal (left) and distal (right) locations*

A total of five different irradiation and cooling conditions were performed in MARS:

- 10-year irradiation, 30-day decay
- 10-year irradiation, 20-year decay
- 1-year irradiation, 30-day decay
- 1-year irradiation, 10-year decay
- 30-day irradiation, 4-hour decay (carbon steel only)

The 10-year and 1-year irradiation times address newer and older material installations. A 30-day decay addresses those items taken out of the beamline and identified as needing a clearance survey in a relatively short amount of time. The longer decay times of 10 years and 20 years address those legacy items stored onsite that require a clearance survey prior to transferring to any location accessible to the public. The 30-day irradiation and 4-hour decay condition for carbon steel addresses those items originating from experimental areas frequently moving and handling potentially radioactive material, such as the MTest and MCenter beamlines at the FTBF.

The MARS results produced several radionuclides not previously covered: ^{44}Ti/^{44}Sc, ^{52}Mn, and ^{56}Mn. These radionuclides are readily detectable gamma emitters that can serve as proxy radionuclides. Proxy radionuclides emit high-yield and high-energy gammas such that they dominate the dose rate on the item's surface—each of these radionuclides emits at least one high-energy gamma at 90% or greater abundance (see Table 5.13). Of note are the radionuclides ^{44}Ti and ^{44}Sc which exist in secular equilibrium: the quantity of ^{44}Sc remains constant because its production rate (due to the decay of ^{44}Ti) is equal to its decay rate.

Table 5.13 *Additional Proxy Radionuclides present in carbon steel*

Material	Radionuclide	Half-Life	Decay Mode	Gamma Energy (keV)
Carbon Steel	^{44}Ti/^{44}Sc	59.1 y / 3.97 h	ε, γ, x / ε, γ	67.9 (93%), 78.3 (96.4%) / 511 (188%), 1157 (99.9%)
Carbon Steel	^{52}Mn	5.6 d	ε, γ, x	511 (58.8%), 744 (90%), 935 (94.5%), 1434 (100%)
Carbon Steel	^{56}Mn	2.6 h	β^-, γ	847 (98.8%), 1811 (26.9%), 2113 (14.2%)

The induced radioactivity profiles for carbon steel and concrete are shown in Tables 5.14 – 5.19. In each table, the radionuclides are listed in descending order, with the radionuclide contributing most to the total activity listed first. Radionuclides contributing to more than 5% of the total radioactivity are shown; however, for those conditions that do not have a proxy radionuclide present above 5%, additional radionuclides were included in the profile until a proxy radionuclide was reached. The SL Fraction has been expressed as a percentage of the total dose risk of the corresponding induced radioactivity profile for the radionuclides listed.

Table 5.14 *Induced radioactivity for carbon steel beam pipe irradiated for ten years*

		30-DAY DECAY		20-YEAR DECAY	
	Energy	**Radionuclide (Radioactivity in %)**	**SL Fraction**	**Radionuclide (Radioactivity in %)**	**SL Fraction**
Proximal	400 MeV	^{55}Fe (58.10%)	0.03%	^{3}H (65.45%)	2.83%
		^{54}Mn (20.57%)	99.91%	^{55}Fe (32.04%)	0.14%
		^{51}Cr (6.55%)	0.03%	^{44}Ti/^{44}Sc (2.25%)	97.04%
		^{49}V (6.31%)	0.03%		
	8 GeV	^{55}Fe (50.30%)	0.03%	^{3}H (75.12%)	1.23%
		^{54}Mn (18.41%)	99.86%	^{55}Fe (17.30%)	0.03%
		^{49}V (11.79%)	0.06%	^{44}Ti/^{44}Sc (6.01%)	98.74%
		^{51}Cr (8.39%)	0.05%		
	120 GeV	^{55}Fe (50.68%)	0.03%	^{3}H (72.58%)	1.09%
		^{54}Mn (18.84%)	99.87%	^{55}Fe (19.06%)	0.03%
		^{49}V (11.79%)	0.06%	^{44}Ti/^{44}Sc (6.57%)	98.88%
		^{51}Cr (8.26%)	0.04%		
Distal	400 MeV	^{55}Fe (81.98%)	0.07%	^{55}Fe (71.64%)	1.11%
		^{54}Mn (11.80%)	99.93%	^{3}H (27.62%)	4.30%
				^{44}Ti/^{44}Sc (0.61%)	94.59%
	8 GeV	^{55}Fe (68.39%)	0.05%	^{3}H (63.34%)	2.05%
		^{54}Mn (14.92%)	99.92%	^{55}Fe (32.98%)	0.11%
		^{49}V (5.36%)	0.04%	^{44}Ti/^{44}Sc (3.02%)	97.84%
	120 GeV	^{55}Fe (69.11%)	0.05%	^{3}H (62.86%)	2.38%
		^{54}Mn (14.51%)	99.92%	^{55}Fe (33.88%)	0.13%
		^{49}V (5.27%)	0.04%	^{44}Ti/^{44}Sc (2.58%)	97.49%

Table 5.15 *Induced radioactivity for carbon steel beam pipe irradiated for one year*

		30-DAY DECAY		10-YEAR DECAY	
	Energy	**Radionuclide (Radioactivity in %)**	**SL Fraction**	**Radionuclide (Radioactivity in %)**	**SL Fraction**
Proximal	400 MeV	^{55}Fe (33.95%)	0.01%	^{55}Fe (86.39%)	2.89%
		^{54}Mn (27.48%)	76.60%	^{3}H (12.89%)	4.31%
		^{51}Cr (15.76%)	0.04%	^{54}Mn (0.28%)	92.80%
		^{56}Co (8.37%)	23.32%		
		^{49}V (8.14%)	0.02%		
	8 GeV	^{55}Fe (27.79%)	0.01%	^{55}Fe (74.47%)	0.72%
		^{54}Mn (23.26%)	99.84%	^{3}H (23.64%)	2.29%
		^{51}Cr (19.07%)	0.08%	^{44}Ti/^{44}Sc (1.00%)	96.99%
		^{49}V (14.37%)	0.06%		
	120 GeV	^{55}Fe (28.01%)	0.01%	^{55}Fe (76.71%)	0.73%
		^{54}Mn (23.81%)	99.85%	^{3}H (21.34%)	2.03%
		^{51}Cr (18.80%)	0.08%	^{44}Ti/^{44}Sc (1.02%)	97.24%
		^{49}V (14.37%)	0.06%		
Distal	400 MeV	^{55}Fe (63.22%)	0.03%	^{55}Fe (97.04%)	6.97%
		^{54}Mn (20.80%)	97.27%	^{3}H (2.73%)	1.96%
		^{59}Fe (5.73%)	2.68%	^{54}Mn (0.13%)	91.06%
		^{51}Cr (5.48%)	0.03%		
	8 GeV	^{55}Fe (45.42%)	0.02%	^{55}Fe (87.07%)	4.50%
		^{54}Mn (22.66%)	99.89%	^{3}H (12.22%)	6.32%
		^{51}Cr (11.56%)	0.05%	^{54}Mn (0.17%)	89.18%
		^{49}V (7.85%)	0.03%		
	120 GeV	^{55}Fe (46.21%)	0.02%	^{55}Fe (87.49%)	4.67%
		^{54}Mn (22.18%)	99.89%	^{3}H (11.86%)	6.33%
		^{51}Cr (11.32%)	0.05%	^{54}Mn (0.17%)	89.00%
		^{49}V (7.77%)	0.04%		

Table 5.16 *Induced radioactivity for carbon steel beam pipe: 30-day irradiation, 4-hour decay*

	PROXIMAL		DISTAL	
Energy	**Radionuclide (Radioactivity in %)**	**SL Fraction**	**Radionuclide (Radioactivity in %)**	**SL Fraction**
400 MeV	^{52}Mn (29.96%)	67.35%	^{56}Mn (58.75%)	43.15%
	^{51}Cr (22.39%)	0.50%	^{64}Cu (7.77%)	0.57%
	^{56}Mn (11.63%)	2.62%	^{52}Mn (7.58%)	55.70%
	^{48}V (7.52%)	16.90%	^{51}Cr (7.19%)	0.53%
	^{55}Co (5.62%)	12.63%	^{55}Fe (6.99%)	0.05%
8 GeV	^{52}Mn (23.95%)	65.08%	^{56}Mn (38.12%)	15.86%
	^{51}Cr (23.93%)	0.65%	^{51}Cr (13.95%)	0.58%
	^{48}V (12.62%)	34.27%	^{52}Mn (13.28%)	55.24%
			^{48}V (6.81%)	28.33%
120 GeV	^{52}Mn (24.23%)	64.82%	^{56}Mn (39.50%)	17.21%
	^{51}Cr (24.13%)	0.65%	^{51}Cr (13.49%)	0.59%
	^{48}V (12.91%)	34.54%	^{52}Mn (12.41%)	54.07%
			^{48}V (6.40%)	27.90%
			^{64}Cu (5.27%)	0.23%

Some conclusions that may be drawn from Tables 5.14 – 5.16 include:

1. For both 1-year and 10-year irradiation of carbon steel with a 30-day decay, the proxy radionuclide ^{54}Mn dominates the total dose risk, while hard-to-measure ^{55}Fe is insignificant though it has higher radioactivity.
2. For shorter irradiation and decay times of carbon steel, proxy radionuclides ^{52}Mn and ^{56}Mn (for distal cases) contribute the most to the total radioactivity and the total dose risk.
3. For a 1-year irradiation and 10-year decay of carbon steel, ^{55}Fe and ^{3}H contribute the most to the total radioactivity, but proxy radionuclides dominate the total dose risk: ^{54}Mn (~90%) for all distal energies and 400 MeV proximal, ^{44}Ti/^{44}Sc (~97%) for 8 GeV and 120 GeV proximal cases.
4. For a 10-year irradiation and 20-year decay of carbon steel, ^{3}H and ^{55}Fe contribute the most to the total radioactivity at all energies for both proximal and distal cases. However, the proxy radionuclides ^{44}Ti/^{44}Sc contribute to > 94% of the total dose risk for all conditions.

Table 5.17 *Induced radioactivity for concrete irradiated for ten years*

		30-DAY DECAY		20-YEAR DECAY	
	Energy	**Radionuclide (Radioactivity in %)**	**SL Fraction**	**Radionuclide (Radioactivity in %)**	**SL Fraction**
Proximal	400 MeV	^{45}Ca (27.21%)	0.25%	^{3}H (97.28%)	11.13%
		^{3}H (20.20%)	0.19%	^{22}Na (0.78%)	88.73%
		^{37}Ar (17.06%)	0.16%		
		^{22}Na (10.55%)	98.41%		
		^{7}Be (10.52%)	0.98%		
		^{55}Fe (8.86%)	0.01%		
	8 GeV	^{3}H (26.56%)	0.25%	^{3}H (97.93%)	14.52%
		^{45}Ca (22.10%)	0.21%	^{39}Ar (0.60%)	0.09%
		^{37}Ar (15.43%)	0.15%	^{22}Na (0.58%)	85.39%
		^{7}Be (13.50%)	1.29%		
		^{22}Na (10.24%)	98.09%		
		^{55}Fe (7.37%)	0.01%		
	120 GeV	^{45}Ca (28.90%)	0.34%	^{3}H (97.82%)	16.63%
		^{3}H (25.84%)	0.30%	^{55}Fe (0.63%)	0.01%
		^{37}Ar (12.95%)	0.15%	^{39}Ar (0.58%)	0.10%
		^{7}Be (11.68%)	1.35%	^{22}Na (0.49%)	83.26%
		^{22}Na (8.48%)	97.86%		
		^{55}Fe (8.45%)	0.01%		
Distal	400 MeV	^{45}Ca (57.10%)	1.23%	^{3}H (91.43%)	9.13%
		^{55}Fe (14.77%)	0.03%	^{41}Ca (2.40%)	23.96%
		^{37}Ar (10.00%)	0.02%	^{22}Na (0.67%)	66.86%
		^{3}H (9.53%)	0.21%		
		^{22}Na (4.56%)	98.51%		
	8 GeV	^{45}Ca (34.88%)	0.44%	^{3}H (96.91%)	14.43%
		^{3}H (22.60%)	0.28%	^{41}Ca (0.65%)	9.68%
		^{37}Ar (13.07%)	0.16%	^{22}Na (0.51%)	75.75%
		^{55}Fe (10.17%)	0.01%		
		^{7}Be (9.12%)	1.15%		
		^{22}Na (7.78%)	97.95%		
	120 GeV	^{45}Ca (37.74%)	0.53%	^{3}H (97.08%)	15.69%
		^{3}H (22.63%)	0.32%	^{41}Ca (0.69%)	11.22%
		^{37}Ar (11.95%)	0.17%	^{22}Na (0.45%)	73.09%
		^{55}Fe (10.16%)	0.01%		
		^{7}Be (8.41%)	1.19%		
		^{22}Na (6.91%)	97.77%		

Table 5.18 *Induced radioactivity for concrete irradiated for one year*

		30-DAY DECAY		10-YEAR DECAY	
	Energy	**Radionuclide (Radioactivity in %)**	**SL Fraction**	**Radionuclide (Radioactivity in %)**	**SL Fraction**
Proximal	400 MeV	^{45}Ca (36.7%)	0.77%	^{3}H (79.50%)	0.77%
		^{37}Ar (29.2%)	0.61%	^{22}Na (10.23%)	99.22%
		^{7}Be (17.8%)	3.73%	^{55}Fe (9.46%)	0.01%
		^{22}Na (4.5%)	94.89%		
	8 GeV	^{3}H (27.18%)	0.25%	^{3}H (85.13%)	1.04%
		^{45}Ca (22.62%)	0.21%	^{22}Na (8.08%)	98.95%
		^{37}Ar (15.79%)	0.15%	^{55}Fe (6.41%)	0.01%
		^{7}Be (13.82%)	1.29%		
		^{22}Na (10.48%)	98.09%		
		^{55}Fe (7.54%)	0.01%		
	120 GeV	^{45}Ca (39.00%)	1.00%	^{3}H (85.00%)	1.22%
		^{37}Ar (22.14%)	0.57%	^{55}Fe (7.54%)	0.01%
		^{7}Be (19.80%)	5.07%	^{22}Na (6.87%)	98.77%
		^{3}H (5.62%)	0.14%		
		^{22}Na (3.64%)	93.23%		
Distal	400 MeV	^{45}Ca (67.62%)	3.74%	^{3}H (63.83%)	0.84%
		^{37}Ar (16.20%)	0.09%	^{55}Fe (26.90%)	0.04%
		^{55}Fe (5.29%)	0.03%	^{22}Na (7.55%)	99.13%
		^{7}Be (4.49%)	2.48%		
		^{3}H (1.78%)	0.10%		
		^{22}Na (1.69%)	93.56%		
	8 GeV	^{45}Ca (46.39%)	1.32%	^{3}H (82.86%)	1.17%
		^{37}Ar (22.01%)	0.63%	^{55}Fe (10.12%)	0.01%
		^{7}Be (15.24%)	4.33%	^{22}Na (7.02%)	98.82%
		^{3}H (4.84%)	0.14%		
		^{55}Fe (4.17%)	0.01%		
		^{22}Na (3.29%)	93.58%		
	120 GeV	^{45}Ca (50.13%)	1.60%	^{3}H (82.97%)	1.31%
		^{37}Ar (20.10%)	0.64%	^{55}Fe (10.11%)	0.02%
		^{7}Be (14.05%)	4.47%	^{22}Na (6.24%)	98.67%
		^{3}H (4.84%)	0.15%		
		^{55}Fe (4.16%)	0.01%		
		^{22}Na (2.92%)	93.12%		

The scenario of concrete with a short irradiation time (30 days) and decay period (4 hours) was not considered a likely scenario. Concrete within enclosures is typically used as shielding material and would be expected to be irradiated for at least one year.

Some conclusions that may be drawn from Tables 5.17 – 5.18 include:

1. For both 1-year and 10-year irradiation of concrete, the proxy radionuclides ^{22}Na dominates the total dose risk, while hard-to-measure radionuclides (e.g., ^{3}H, ^{45}Ca, and ^{55}Fe) are insignificant from a dose risk perspective even though they have higher radioactivity.

2. After about 20-years of decay, hard-to-measure radionuclides ^{3}H and ^{41}Ca begin to comprise a larger percent of the total dose risk, because the shorter-lived proxy radionuclides ^{22}Na and ^{54}Mn will decay at a faster rate. This is a limitation for legacy concrete.

3. While not included in the composition of the concrete for the Fermilab MARS modeling, ^{152}Eu and ^{60}Co can often be measured in activated concrete due their large thermal neutron cross sections. The radioactivity level of ^{152}Eu and ^{60}Co depends strongly on thermal neutron fluence and the trace concentrations of europium and cobalt in the concrete; however, this provides additional assurance in the IFB approach for measurements in concrete.

5.3.2.4 Surface contamination at Fermilab

Surface contamination at Fermilab is typically found in large air gaps of the primary beam and any location where the particle flux is high enough to create significant spallation in air with comparatively low air flow. The dominant radionuclide of concern for surface contamination in these areas is ^{7}Be. The areas where ^{7}Be is suspected include:

1. The Main Injector abort face, the MTA/ITA air gap and target box, and inside the MTA abort cave

2. High loss areas such as collimators that, depending on the energy of the beam, are mainly contained to the beam pipe

3. Beam pipes where there are losses due to missteering of the beam or continued running with a magnet failure

4. Absorber blocks in the MI12 decay pipe

Tritium contamination is possible in certain circumstances. Examples include equipment containing water, oil, or other liquids that may be activated. Additionally, items from water systems previously containing tritium concentrations greater than 100 pCi/mL (e.g., Radioactive Water [RAW], some sections of Industrial Cooling Water [ICW], and NuMI condensate system) require monitoring for tritium surface contamination.

Any area with the potential for surface contamination is posted as a Contamination Area. When exiting areas not posted as a Contamination Area, radiological workers will survey their hands and feet for contamination (as well as any objects that were brought into the area), but do not expect to see the presence of contamination.

5.3.2.5 Summary

The characteristics of induced radionuclides that form the technical basis of Fermilab measurement protocols are summarized as follows [DOE 2016, SLAC 2011b]:

1. Many radionuclides can be produced from prompt radiation, but most of them have short half-lives and decay quickly (within days or weeks). The most abundant radionuclides are those with long half-lives on the order of the beam irradiation time, e.g., months to years.
   - ***This justifies the measurement of radionuclides with medium to long half-lives for all items onsite, with the rare exception of certain items originating from the FTBF and ITA.***

2. Radionuclides with either atomic number or mass number lower than their parent nuclides can be produced (except radionuclides produced from thermal neutron absorption), but none are alpha emitters. Most residual radionuclides emit beta and gamma radiation which can be easily measured with common radiation instruments
   - ***This justifies the measurement of beta-gamma radionuclides.***

3. Radionuclides that emit pure beta or low-energy or low-yield photons (which are hard to measure) are accompanied by proxy radionuclides that emit high-yield, high-energy gamma rays (which can be measured easily).
   - ***This justifies the measurement of proxy radionuclides, instead of measurements of all potential radionuclides that can be produced.***

4. Proxy radionuclides contribute to most (if not all) of the surface dose rate due to their high gamma yields and energies.
   - Proxy radionuclides in metals include ^{22}Na, ^{44}Ti/^{44}Sc, ^{52}Mn, ^{54}Mn, ^{56}Mn, and ^{60}Co.
   - Proxy radionuclides in concrete include ^{22}Na and ^{54}Mn, as well as ^{60}Co, ^{152}Eu and ^{154}Eu from thermal neutron capture reaction of trace elements.

5. Hard to measure radionuclides include ^{3}H, ^{7}Be, ^{41}Ca, ^{45}Ca, ^{51}Cr, ^{55}Fe, and ^{63}Ni.

6. The hard-to-measure radionuclides ^{3}H, ^{41}Ca, ^{45}Ca, ^{51}Cr, ^{55}Fe can exist in metals and particularly in concrete. However, their dose risks (when normalized to the ANSI SL values) are substantially smaller than the dose risks presented by proxy radionuclides. Therefore, their potential existence can be indirectly estimated by the measurements of proxy radionuclides.
   a. The exception to this is graphite, where, due to graphite's low atomic number, only ^{3}H is produced and no proxies can be used.
   b. If a concrete block has decayed for over 20 years, ^{3}H (12.3-yr half-life) and ^{41}Ca (99400-year half-life) activity will become more than 200 times higher than ^{22}Na (2.6-yr half-life) activity and increasingly dominate the dose risk as ^{22}Na decays. Potential solutions are to:
      i. Collect a core sample pre-processed with a combustion oxidation and count with LSC or mass spectroscopy; or,
      ii. Surface swipe for ^{3}H with LSC measurement, for proximal concrete where ^{41}Ca is not prominent.

7. In copper, ^{60}Co at all activation energies serves as an adequate proxy for ^{63}Ni (whose activity is 10 times higher than ^{60}Co) and ^{3}H (whose activity is < 1/10 of ^{60}Co) for 30 days decay [DOE 2016]. However, after 30-40 years decay, there may no longer be an adequate proxy for them at lower beam energies, as the easily-detectable radionuclides decay more quickly (e.g., ^{60}Co proxy decays to a level that is a factor of 1,000 less than ^{63}Ni at 30 years, ~6 half-lives of ^{60}Co, for the worst case of 17-MeV proton beam). For higher beam energies, ^{60}Co is a good proxy for at least 50 years decay. In this case, if the detection technique is demonstrated to be sufficient for ^{60}Co, it is sufficient for all radionuclides in most proton beam energy, irradiation time and decay time conditions.

8. ^{7}Be decays by electron capture, and the only radiation produced in sufficient yield to be useful in measurement is a gamma ray, about 477.6 keV in energy and with a yield of 0.1044 gammas per disintegration of the ^{7}Be. It is produced not only by atmospheric spallation from accelerator-produced (and cosmic ray-produced) neutrons and protons, but also as a reaction with aluminum via ^{27}Al(p,11n+10p)^{7}Be. ^{22}Na can be used as a proxy for volumetric activation of aluminum. For surface contamination, the choice of instrument for detecting this hard-to-measure gamma ray depends on the expected quantities or concentrations being assessed and whether other radionuclides are present along with the ^{7}Be. See Appendix C.2.3 for details.

9. The induced radioactivity in any solid object will present its maximum concentration at or near the surface that faces the beam loss point.
   - ***This justifies using surface (scanning and fixed position) measurements for volumetric radioactivity.***

10. There are commercially available portable instruments, such as scintillator-based survey meters, that have detection thresholds or limits for proxy radionuclides that are less than the corresponding ANSI N13.12-2013 SL values.
    - ***This justifies the use of sensitive, portable survey meters for volumetric radioactivity measurements.***

5.3.3 Measurement Methods

Fermilab measurement protocols include measurements for both surface contamination and volumetric radioactivity using appropriate radiation detection instruments and procedures in an ambient environment with an acceptably low background. In general, if an item is determined to be impacted through process knowledge, it will be surveyed for volumetric contamination (activation). Additionally, if process knowledge indicates that surface contamination is possible as determined by the assigned RSO, it will be surveyed for removable contamination and/or total contamination. A percentage of impacted items will undergo confirmatory measurements. The details of these measurements are described below.

The chosen survey instrument shall have a current calibration and operate within recommended environmental conditions. Only personnel with appropriate training and qualification can take measurements. Training must be commensurate with the general and specific measurement scope, purpose, and methods. Personnel training is conducted and refreshed at regular intervals and documented in the TRAIN training database.

5.3.3.1 Measurement for Surface Radioactivity

The Fermilab measurement protocol for surface contamination measurements is a combination of scanning and static measurements with a pancake GM detector like those shown in Figure 5.7, supplemented with surface swipe sampling methods to distinguish removable contamination from total (or volumetric) contamination. However, operational experience shows that surface contamination is limited to only a few places and the radiation at those locations is also dominated by the volumetric radioactivity of the proxy radionuclides (i.e., alpha and pure beta radiation fields are not present).

Surface surveys for volumetric radioactivity may be sufficient such that measurements for surface contamination are not needed, when it can be demonstrated that the surface surveys for volumetric radioactivity are as protective as measurements for surface contamination. For example, if process knowledge shows that surface contamination is minimal and the induced radiation field on an object's surface is dominated by the volumetric radioactivity of the proxy radionuclides (e.g., there are no radionuclides emitting alpha, pure beta, or low-energy or low-yield photons), surface surveys for volumetric radioactivity alone may demonstrate that both ANSI volume and surface SLs are satisfied [DOE 2016].

Therefore, unless removable contamination is suspected, volumetric radioactivity measurements can be used in lieu of surface radioactivity measurements, as they prove as protective as using surface measurements. In the event Fermilab chooses to use a pancake GM detector to measure for contamination, appropriate survey instrumentation has been selected, and each can achieve sensitivities that satisfy the surface contamination limits in Figure IV-1 of DOE Order 5400.5. The detection thresholds for surface radioactivity are summarized in Tables 5.19 and 5.20 and documented in Appendix C.

If an item has been in a Contamination Area, it automatically receives measurements for the presence of removable contamination. If an item originates from an area where ^{3}H contamination is suspected, it must have ^{3}H measurements performed (details in Appendix C.2.2). If an item originates from an area where ^{7}Be contamination is suspected, it must have ^{7}Be measurements performed (details in Appendix C.2.3).

Figure 5.7 *Fermilab measurement instruments for surface contamination: Ludlum 177-4 (left) and Eberline E140N (right), both with Ludlum 44-9 pancake GM detector*

Table 5.19 *Fermilab measurement protocols and detection thresholds for total (fixed + removable) contamination*

Measurement Instrument	Measurement Protocol	Detection Threshold
Ludlum 177-4 w/44-9 pancake GM	1. For beta-gamma contamination 2. Perform a 1-minute background, must be ≤ 80 cpm 3. Scan entire surface area of item at 1"/s within ¼" of surface 4. Perform at least one 1-minute static count per 1 m^2 surface area at potential elevated area(s) or in a representative area if no elevated reading detected on scan	Static: 2161 dpm/100 cm^2 Scanning: 4877 dpm/100 cm^2 DOE Order 5400.5 Authorized Limit for beta-gamma emitters = 5,000 dpm/100 cm^2
Eberline E140N w/44-9 pancake GM	1. For beta-gamma contamination 2. Perform a 1-minute background, must be ≤ 50 cpm 3. Scan entire surface area of item at 1"/s within ¼" of surface 4. Perform at least one 1-minute static count per 1 m^2 surface area at potential elevated area(s) or in a representative area if no elevated reading detected on scan	Static: 1709 dpm/100 cm^2 Scanning: 3855 dpm/100 cm^2 DOE Order 5400.5 Authorized Limit for beta-gamma emitters = 5,000 dpm/100 cm^2

Table 5.20 *Fermilab measurement protocols and detection thresholds for removable contamination analyzed by the Radionuclide Analysis Facility (RAF)*

Measurement Instrument	Measurement Protocol	Detection Threshold
PROXY RADIONUCLIDES		
Alpha/Beta Gas-Flow Proportional Counter	1. Swipe 100 cm^2 area 2. Count swipe for 1 minute 3. Used when deemed warranted by process knowledge	52 dpm/100 cm^2 DOE Order 5400.5 Authorized Limit for beta-gamma emitters = 1,000 dpm/100 cm^2
TRITIUM		
Liquid Scintillation Counter (LSC)	1. Swipe 100 cm^2 area 2. Count swipe with LSC for 2 hours 3. Used when deemed warranted by process knowledge	< 10 dpm/100 cm^2 10 CFR 835 removable surface contamination value for tritium and STCs = 10,000 dpm/100 cm^2
BERYLLIUM-7		
HPGe Gamma Spectrometer	1. Swipe 100 cm^2 area 2. Count swipe for 1 hour 3. Used when deemed warranted by process knowledge	699 dpm/100 cm^2 DOE Order 5400.5 Authorized Limit for beta-gamma emitters = 1,000 dpm/100 cm^2
Alpha/Beta Gas-Flow Proportional Counter	1. Swipe 100 cm^2 area 2. Count swipe for 1 hour 3. Used when deemed warranted by process knowledge	603 dpm/100 cm^2 DOE Order 5400.5 Authorized Limit for beta-gamma emitters = 1,000 dpm/100 cm^2
RESERVED	*RESERVED*	*RESERVED*

5.3.3.2 Measurement for Volumetric Radioactivity

Volumetric measurements are used when the potential for volumetric radioactivity cannot be excluded by process knowledge. Volumetric radioactivity for proxy radionuclides is measured using a Bicron Analyst with 1.5” diameter × 1” thick NaI(Tl) detector in an environment with an acceptable background (see Figure 5.8). Measurements (scans and fixed-position) shall be taken on all surfaces of a component, regardless of its shape and size, with the exception that a measurement of a single surface of a component that faces a beam loss point is also acceptable if the beam loss geometry is known.

Figure 5.8 *Bicron Analyst with 1.5" x 1" NaI(Tl) detector used for volumetric activation measurements*

IFB is achieved if the measurement detects no radioactivity above natural background and the corresponding critical concentration is less than the ANSI SL value. As shown in Appendix B, the detection thresholds of the Fermilab volumetric radioactivity measurements for proxy radionuclides were determined to be 0.7 – 2.3 pCi/g for surface measurements using the 1.5" x 1" NaI(Tl) detector, which is less than the corresponding ANSI SL value for Group 1 radionuclides (3 pCi/g). Table 5.21 summarizes the Fermilab measurement protocols for volumetric activation.

If there are inaccessible surfaces that are closest to the beam or beam loss point, process knowledge is used and/or disassembly of the item is performed to gain access to all surfaces. If inaccessible surfaces cannot be accessed and process knowledge is not adequate for material release, the item shall not be released.

Table 5.21 *Fermilab measurement protocol and detection thresholds for volumetric radioactivity*

Measurement Instrument	Measurement Protocol	Detection Threshold
Bicron Analyst with 1.5" x 1" NaI(Tl) detector	1. Perform a 1-minute background count, must be ≤ 3000 cpm 2. Scan item at 2"/s within 1 cm of surface 3. Perform at least one 1-minute static count per 1 m^2 surface area at potential elevated area(s) or in a representative area if no elevated reading detected on scan 4. Survey entire surface area or on surface facing beam loss point (if known) 5. If net counts are less than level shown in Table 5.22, the item is IFB	0.7 – 2.3 pCi/g for proxy radionuclides (^{22}Na, ^{60}Co) ANSI N13.12-2013 SL for Group 1 radionuclides = 3 pCi/g

Table 5.22 *Background-dependent detection thresholds for IFB determination of volumetric radioactivity*

Background (cpm)	IFB Detection Threshold (net cpm)	Background (cpm)	IFB Detection Threshold (net cpm)	Background (cpm)	IFB Detection Threshold (net cpm)
1000	**147**	1700	**191**	2400	**227**
1100	**154**	1800	**197**	2500	**232**
1200	**161**	1900	**202**	2600	**237**
1300	**167**	2000	**207**	2700	**241**
1400	**173**	2100	**213**	2800	**246**
1500	**180**	2200	**218**	2900	**250**
1600	**186**	2300	**223**	3000	**254**

5.3.3.3 Confirmatory Measurements

Fermilab utilizes confirmatory measurements to supplement or validate the surface measurements for volumetric radioactivity, including gamma spectrometry in the field, laboratory analysis of representative samples of the item using low-background high-purity germanium (HPGe), or a portal gate monitor. Confirmatory measurement is a best management practice and is conducted, as warranted, using a graded approach based on considerations of process knowledge and ALARA.

The Fermilab confirmatory measurements provide lower detection thresholds for proxy radionuclides, ranging from 0.1-1 pCi/g [DOE 2016]. These limits apply to environmental samples, where the expectation is to have environmental levels of radioactivity (i.e., little to no radioactivity is present). Table 5.23 summarizes Fermilab's confirmatory measurement capabilities. See Appendix B.2 for details.

Table 5.23 *Fermilab confirmatory measurement detection thresholds for volumetric radioactivity*

Method	Equipment & Method to Detect Proxy Radionuclides	DTs for Proxy Radionuclides[1]
Field gamma spectrometry	Surface measurements using a portable gamma spectrometer for radionuclides in the fixed-position measurement mode	< 1.0 pCi/g
Laboratory HPGe measurements of representative samples	Representative samples collected and counted using low-background HPGe system with the environmental counting protocol in a standard counting geometry	< 0.1 pCi/g
Portal gate monitor	Vehicles transporting bulk items regulated by this document (i.e., scrap metal) pass through a scintillation detector portal monitor	< 1.0 µCi ^{60}Co

[1] ANSI SL is 3 pCi/g for proxy radionuclides

A few guidelines for the use of confirmatory measurements include [SLAC 2011b]:

- For large concrete blocks (e.g., greater than a few cubic feet), field gamma spectrometry and/or radioanalysis laboratory sample measurements can be used.
- For large-size metal materials, radioanalysis laboratory sample measurements are often not practical and field gamma spectrometry can be used.
- For individual small metal materials or concrete blocks, a surface survey may be sufficient (e.g., a slower speed scan or a fixed-position survey with a longer time can be used to lower the DT, making confirmatory measurements unnecessary).
- For small items grouped in a batch (such as cables, wires, or bolts), field gamma spectrometry can be used in addition to the surface survey.
- The frequency of confirmatory measurements should be **high**:
  - For materials that are close to a beam loss point and likely to have a high-gradient volumetric radioactivity profile (e.g., vacuum chamber or magnets near beam absorbers or collimators).
  - For materials that are known to be radiologically impacted.
- The frequency of confirmatory measurements can be **low**:
  - For materials that are not close to a beam loss point and likely to have a low-gradient or slowly varying volumetric radioactivity profile (e.g., concrete walls or metal shielding)
  - For materials that have no or minimal potential to be radiologically impacted.

Fermilab reserves the option to utilize one or more additional controls as appropriate to help verify that concrete and metal materials leaving the site are free of radioactivity. These measures can include additional surveys or measurements.

It is possible that a confirmatory measurement with a lower detection threshold than that of a field survey measurement can identify materials with detectable radioactivity that were undetected with the field survey. When that situation occurs, the material is not released, and all related field survey and confirmatory measurement results and records are thoroughly reviewed. The causes are investigated, and an extent of condition review is also conducted.

5.3.4 Graded approach and MARSSIM and MARSSAME Considerations

The Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM) is a multi-agency consensus document that provides guidance for planning, implementing, and evaluating environmental and facility radiological surveys conducted to demonstrate compliance with a dose or risk-based regulation [MARS 2002]. The exposure pathway models used to obtain site-specific release criteria are not part of MARSSIM.

The Multi-Agency Radiation Survey and Assessment of Materials and Equipment Manual (MARSAME) is a supplement to MARSSIM [MARS 2009]. It provides guidance for planning, conducting, evaluating, and documenting radiological disposition surveys for the assessment of materials and equipment. It describes a statistical method for obtaining survey data and comparing them, on a pass-fail basis, to a release criterion. Specific guidance (not requirements) in MARSAME includes assessment of materials and equipment, survey design and implementation (such as field survey methods, instrumentation, data quality objectives, measurement quality objectives), result evaluation and reporting, and quality

assurance/quality control. Fermilab developed the measurement protocols in this technical basis document following the guidance in DOE-STD-6004, which is based on MARSSIM and MARSAME approaches. Facility-specific RPP procedures will also follow the guidance in DOE-STD-6004.

Process knowledge evaluation allows for area zoning and component identification, both of which are useful for planning and optimizing the measurement process in a graded approach [SLAC 2011b]. For example, areas at Fermilab that have no reasonable potential for materials present in the area to become activated or contaminated with radioactivity above background can be classified as **non-impacted areas**. Non-impacted areas may include the areas outside accelerator enclosures, klystron areas, and any non-radiologically posted area. Non-impacted areas do not need the level of survey coverage required by this document because they have no potential for residual radioactivity.

Areas where there is a reasonable potential for M&E within the area to become activated or contaminated with radioactivity above background are classified as **impacted areas**. Impacted areas include accelerator enclosures, particularly areas within accelerator enclosures containing beam intercepting devices such as absorbers, collimators, septa, and injection/extraction equipment. Impacted M&E also includes radioactive material outside of accelerator enclosures and any equipment with activated air or water that is potentially contaminated above background—equipment containing or having contained tritium in concentrations greater than 100 pCi/mL is under radiological control and considered impacted. Release from impacted areas is subject to the process established by this document. M&E that was brought into an impacted area when the beam was off does not have the potential for activation and can therefore be classified as non-impacted (provided surface contamination is also not a concern). Key impacted areas at Fermilab are indicated in Figure 5.9.

Impacted areas may be further divided into one of four classifications:

- Level 1: Areas *known* to have or have had surface contamination or volumetric activation, based on process knowledge or previous radiological surveys, or both. Examples include areas near normal beam loss points, such as beam absorbers, septa, collimators, and targets.
- Level 2: Areas that have or have had at least a *potential* for surface contamination or volumetric activation, based on process knowledge, previous radiological surveys, or both. Examples include areas located adjacent to Level 1 areas and any area or system handling radioactive effluent.
- Level 3: Areas that have or have had a *minimal potential* for surface contamination or volumetric activation based on process knowledge or previous radiological surveys, or both. Examples include areas that have had no beam losses or preliminary area surveys showed no induced radioactivity.
- Level 4: Areas where ^{3}H or ^{7}Be contamination is suspected.

Level 1 areas have the greatest potential for contamination or activation. Therefore, they must receive the highest degree of survey effort if M&E within them are to be released. Successively smaller levels of effort can be used for Level 2 and Level 3 areas. Level 4 areas must have removable contamination measurements performed per section C.2.

Figure 5.9 *Locations of key impacted areas at Fermilab*

MARSAME statistical concepts allow for the possibility of false positive results by surveying only a certain percentage of a batch or batches of material, depending on classification of the material. MARSSIM places greater survey efforts on areas that have, or had, the highest potential for contamination. This resource distribution consideration is referred to as a graded approach [MARS 2002].

Examples of Fermilab's graded approach include:

- Survey process for different types of areas or components,
- Selection of locations, surfaces, or area of a surface to be surveyed,
- Scanning over the whole surface combined with fixed-position measurements, and
- Use of confirmatory measurements (field gamma spectrometer or representative samples measured by laboratory analysis; see Table 5.23).

5.3.4.1 Surface Survey

When performing a release survey, the surveyor scans over the surface of an item and conducts fixed-position measurements every 1 m^2 at potential elevated area(s) or in a representative area if no elevated reading is detected during the scan. The detectable region of the 1.5" × 1" NaI(Tl) detector depends on the material type and gamma ray energy (Appendix B provides additional details). The concept of "detectable region" has two implications for release measurements:

1. If the object being surveyed is smaller than the detectable region, it needs to be combined with other small items that have similar activation potential as a batch for a survey. SLAC concludes that as the sample volume decreases, the DT increases. Therefore, to achieve a lower DT, the item(s) being surveyed should be of a sufficient volume [SLAC 2011c]. Small items such as bolts or thin wires, which also have similar activation potential, should be surveyed together as a group with a size not less than 16" x 16" for the survey.
2. To detect beyond the detectable region, the surveyor needs to scan over the surface or take fixed-position measurements at distances close to the detectable region. For fixed-position measurements, the minimum distance between two neighboring fixed points can be 10 cm. A survey method can also be a combination of scanning and fixed-position measurements (e.g., scanning along the X direction and fixed intervals in the Y direction).

If there is no process knowledge as to which material surface(s) have not been exposed to contamination or beam, then 100% of all surfaces of an item to be released must be surveyed. If process knowledge determines that those surfaces of the material exposed to beam are known, then only the side of the item facing the beam needs to be surveyed. Process knowledge may dictate that a surface scan is not necessary. For example, components that are not close to the beam loss points, such as concrete shield blocks, will have a smaller and less-variable gradient of the induced radioactivity spatial profile. Therefore, instead of scanning, fixed-position measurements every one (1) meter can be conducted for these types of items, as determined by the assigned RSO [SLAC 2011b].

5.3.4.2 Confirmatory Measurements

As a best management practice, a graded approach is also used to establish the confirmatory measurement requirements. Fermilab assigned RSOs will determine the percentage of material that requires confirmatory measurements on a case-by-case basis, with items originating from Level 1 Areas receiving more scrutiny than those items originating from Level 2 or Level 3 Areas.

Cleared impacted M&E that will be exiting the Fermilab site (e.g., for waste or recycling) should have an additional survey performed. For scrap metal, the vehicle carrying bulk M&E should exit the site via the Ludlum 4525-14000 vehicle gate monitor. For small containers (e.g., drums), a survey of the exterior of the package using a Bicron Analyst in rate meter mode is sufficient.

5.4 Documentation and Records Management

5.4.1 Documents and Records

The following documents and records related to the material release program shall be collected and/or produced:

5.4.1.1 General Program Documentation

- Relevant regulations and standards
- Technical basis documents supporting the program, including:
  - Documents concerning accelerator and facility parameters and operations
  - Documents concerning calculations or evaluations for both surface and induced radioactivity
- Procedures and records for Radiological Area classification, survey and posting
- Procedures for the field characterization of radiological status of the materials
- Procedures and records for instrument calibration and testing
- Procedures and reports for sample collection and laboratory measurements
- Procedures and reports for field gamma spectrometry
- Procedures and records for technician training and qualification for instruments and measurement methods
- Procedures and records for material storage on-site prior to release
- Records of release or disposal decisions (e.g., no potential reuse) and authorization
- Records of stakeholder communication, including reporting to management and regulators

5.4.1.2 Clearance and Release-Specific Documentation

- Specific process knowledge used to support or supplement clearance measurements (i.e., beam parameters and operating conditions, material usage, etc.)
- Historical survey records of the property to be released
- Description of facility and item(s) surveyed
- Radiological survey report that includes measurement conditions and results, date and location of measurements, instrument models and serial numbers, calibration date, background levels, response check results, and measurement conditions and results
- Confirmatory measurement reports, such as gamma spectroscopy and portal gate monitor records, if applicable
- Comments and other correction factors that affect the results
- Date and name of surveyor, as well as the name and signature of the reviewer/approver
- Records of release or disposal decisions (e.g., no potential reuse), the property's destination or disposition, as appropriate, and authorization
- Records of stakeholder communication (if any), including reporting to management and regulators

For large-scale material release projects, the records of item inventory, survey results, on-site reuse or storage, and off-site disposal and release need to be tracked by a standardized system. The documents and records must be managed and maintained for accountability and auditing purposes.

5.4.2 Survey Records

A radiation survey record shall be produced for each measurement resulting in the material release. Survey records shall have the following contents:

- Description of item(s) surveyed
- Instrument models and serial numbers, survey methods, calibration, background levels
- Survey results (with conclusion of detectable radioactivity or not) and date and name of surveyor
- Comments and other correction factors that have effects on the results
- Large items (such as large concrete blocks, accelerator magnets and detector components) are individually identified, labeled, surveyed, and recorded
- Small items (such as cables, wires, small concrete blocks) are surveyed as a batch, collectively identified, labeled, and collectively recorded
- Photos may be used for identification of items

The Fermilab *Radiological Clearance Form* is used to record the results of each clearance survey and constitutes the official record of each such survey [RPP 2022].

5.5 ALARA Considerations

DOE requires potential exposures to the public from all releases to be controlled at ALARA levels and well below the applicable dose limits of 100 mrem/yr. Because Fermilab only releases items that have no detectable volumetric radioactivity and the detection thresholds of Fermilab measurement protocols are less than the ANSI SL values, the potential dose is expected to be less than the ANSI dose criterion of 1 mrem/yr. The radiation risk to the public and the potential impacts to the environment are thus inherently negligible, and the Fermilab release protocol and process is also already ALARA [DOE 2016].

A qualitative ALARA analysis was undertaken for the use of the pre-approved surface contamination limits from DOE O 5400.5. Using the surface contamination pre-approved Authorized Limits provides reasonable assurance that doses are well below the personal property dose constraint of 1 mrem/year or a collective dose of 10 person-rem in a year from DOE O 458.1. The low potential dose risk compared to the cost and difficulties of obtaining more sensitive handheld instrumentation, undergoing laboratory analysis, or using longer measurement protocols justifies the use of the surface contamination pre-approved authorized limits as ALARA.

If in the future Fermilab seeks DOE approval to use authorized limits for clearance of radioactive materials (i.e., unrestricted releases of materials with slight residual radioactivity), ALARA analysis will be conducted in the assessment of doses associated with potential release.

5.6 Stakeholder Communications and Involvement

5.6.1 DOE

An important communication aspect of this document is the appraisal by the FSO of its existence, content, and future revisions. Fermilab will coordinate with FSO for this purpose.

Fermilab will also work and coordinate with the FSO on DOE's verification and validation of the Fermilab material release program, as well as on large material release projects.

For releases of material without detectable radioactivity using IFB criteria, DOE approval is not required. For clearance of slightly radioactive material under authorized limits (a clearance process), Fermilab will secure approval from DOE.

Information regarding materials released under the clearance process will be reported to DOE in the Fermilab Annual Site Environmental Report (ASER) or other DOE-required reporting document, as required by DOE [DOE 2020].

5.6.2 Public

The Fermilab material release program and its associated documents and records are nonconfidential and are regarded as "public information." Information regarding materials released and reported in the ASER or other DOE-required reporting documents is available to the public.

For releases of slightly radioactive material to be conducted under authorized limits (a clearance process), Fermilab will follow the public involvement guidelines in DOE [DOE 2020].

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Appendix A: Detection Sensitivity

The detection sensitivity of a measurement system refers to a radiation level or quantity of radioactive material that can be measured or detected with some known or estimated level of confidence. This quantity is a factor of both the instrumentation and the technique or procedure being used.

When evaluating materials to be released for potential surface or volumetric radioactivity, the terms critical level, detection limit, and minimum detectable concentration are frequently encountered. Their use and understanding are crucial in determining if radioactivity is present in a sample and to what level of confidence that determination is made. These terms will be discussed in the following section.

A.1 Counting Statistics

The critical level (L_C) is the net response level, in counts, at which the detector output can be considered "above background." It is the value at which some percentage of the measurements made on samples containing no activity will show activity above statistical background fluctuations (false-positive indication). The defining equation for L_C is

$$L_C\ (\text{cpm}) = m\sqrt{\frac{R_b}{t_{s+b}} + \frac{R_b}{t_b}}$$

where

m = constant associated with the selected confidence level
R_b = background count rate (cpm)
t_{s+b} = time to count the sample (min)
t_b = time to count the background (min)

The detection limit (L_D) is the net response level, in counts, that can be detected and quantified by a measurement method with a specified confidence. The L_D is the smallest amount of radioactivity that will produce a net count rate which will be detected as being positive a set percentage of the time, typically 95%. The probability of counts from a sample escaping detection is 5% (false-negative result). The defining equation for L_D is

$$L_D\ (\text{cpm}) = \frac{m^2}{t_{s+b}} + 2\,m\sqrt{\frac{R_b}{t_b}\left(1 + \frac{t_b}{t_{s+b}}\right)}$$

Both L_C and L_D are calculated before performing any sample measurements and are only a function of counting system parameters. The L_C and L_D can be calculated using Poisson statistics. For these calculations, two types of decision errors should be considered. A Type I error (false-positive) occurs when a detector response is considered to be above background when, in fact, only background radiation is present. A Type II error (false-negative) occurs when a detector response is considered to be background when, in fact, radiation is present at levels above background. The probability of a Type I error is referred to as α and is associated with L_C; the probability of a Type II error is referred to as β and is associated with L_D. Figure A.1 graphically illustrates the relationship of these terms with respect to each other and to a normal background distribution [MARS 2002].

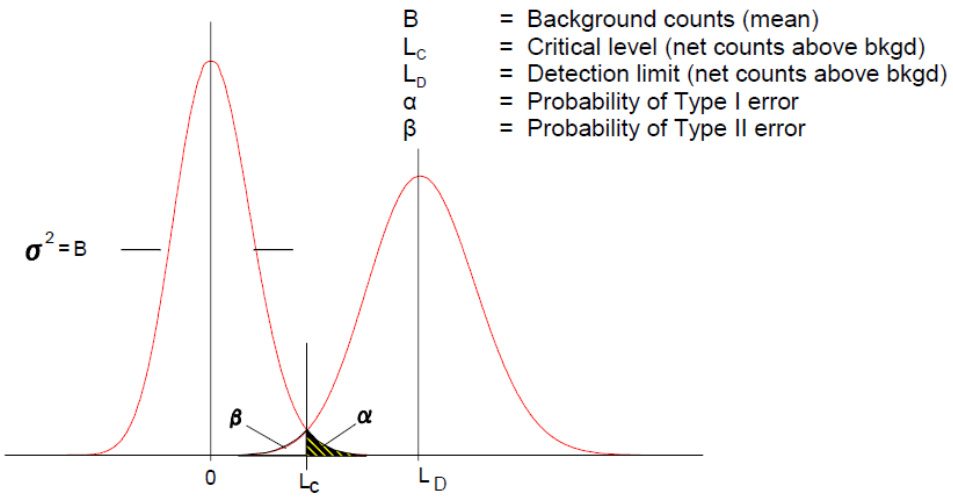

Figure A.1 *Graphically Represented Probabilities for Type I and Type II Errors in Detection Sensitivity for Instrumentation with a Background Response*

The curve to the left in the diagram is the background distribution minus the mean of the background distribution. The result is a Poisson distribution with a mean equal to zero and a variance, σ^2, equal to B. Note that the distribution accounts only for the expected statistical variation due to the stochastic nature of radioactive decay.

The L_D can be converted to an equivalent minimum detectable concentration (MDC). The MDC is calculated before any measurements are made and is used to estimate the level of activity that can be detected using a given protocol. The MDC is dependent not only on the background level and the characteristics of the detector used (such as efficiency and window area), but it also depends on the nature (type and energy of emissions) and relative distribution of potential contamination (point versus distributed source and depth of contamination), and other factors related to the physical survey environment.

This is especially important when performing scan surveys to identify locations of elevated direct radiation that require further investigation. The minimum detectable concentration of a scan survey (scan MDC) also depends on the surveyor's technique (e.g., scan rate) and ability to decide whether the signal represents only the background count response, or more generally, whether detector response in cpm represents residual contamination in excess of noise (i.e., the background detector response).

The following sections consider surveyor technique and ability using the traditional approach for estimating the scan MDC, when surveyors make contamination detection decisions based on the radiation detector's audible output. Three variables are specifically used to describe the surveyor's decision-making abilities: the index of sensitivity (*d'*), the surveyor efficiency (*p*), and the observation interval (*i*).

A.1.1. Human Factors and Scan MDC Calculations

The scan MDC is determined by (1) estimating the net minimum detectable count rate (MDCR) that a surveyor can distinguish from the background detector response, and (2) applying efficiency factors that relate to the surveyor, instrumentation, and source of radiation. Generically, these factors may be mathematically described as follows:

$$\text{Scan MDC} = \frac{\text{MDCR}}{\text{(Surveyor Eff.) x (Instrument Eff.) x (Source Eff.)}}$$

where efficiencies ("Eff.") are used to convert MDCR in cpm to a quantity that is directly comparable to a release criterion (e.g., dpm/100 cm^2 for surface contamination or pCi/g for volumetric activation). Of the above terms, the instrument efficiency is either known (e.g., from the literature) or calculated. The source efficiency may be determined by modeling the radionuclide contamination in a specific geometry and includes considerations of material density and contaminant depth distribution. However, the MDCR and surveyor efficiency are estimated considering human factors that can be challenging to quantify or justify; these two inputs are addressed first because they are produced using the same approach no matter the target medium.

NUREG/CR-6364 [NRC 1998] discusses in detail the human factors as they relate to surveyor performance during scan surveys. These human factors are used to predict a surveyor's ability to identify contamination in the environment using a detector's audio response (i.e., audible "clicks"). Some factors that may affect the surveyor's performance include the costs associated with various outcomes (e.g., the cost of missed contamination versus the cost of incorrectly identifying areas as being contaminated) and the surveyor's expectation of the likelihood of contamination present based on process knowledge. For example, if the surveyor believes that the potential for contamination is very low, as in a presumably unaffected area, a relatively large signal may be required for the surveyor to conclude that contamination is present.

Signal detection theory provides a framework for deciding whether the audible output of the survey meter during scanning resulted from background or signal plus background levels. An index of sensitivity (*d*′) that represents the distance between the means of the background and background plus signal, in units of their common standard deviation, can be calculated for various decision errors—Type I error (α) and Type II error (β). The resulting expression for the ideal observer's MDCR, in cpm, can be written as the following:

$$\text{MDCR} = s_i \, x \left(\frac{60}{i}\right) = d' \sqrt{\left(\frac{R_b}{60}\right) i} \left(\frac{60}{i}\right)$$

where:

MDCR = minimum detectable net count rate for the ideal observer (cpm)
s_i = minimum detectable number of net source counts in the observation interval
d′ = index of sensitivity
R_b = background count rate (cpm)
i = observational interval based on the scan speed and areal extent of the contamination (seconds)

For the non-ideal observer, the surveyor efficiency (*p*) is applied to the minimum detectable number of net source counts (s_i) and, therefore, the MDCR. This term accounts for the real-world condition that the surveyor will perform less efficiently than the ideal observer:

$$\text{MDCR}_{\text{surveyor}} = \frac{s_i \; x \; \left(\frac{60}{i}\right)}{\sqrt{p}} = \frac{d' \sqrt{\left(\frac{R_b}{60}\right) i} \; \left(\frac{60}{i}\right)}{\sqrt{p}}$$

The generic scan MDC equation may now be rewritten as follows:

$$\text{Scan MDC} = \frac{d' \sqrt{\left(\frac{R_b}{60}\right) i} \; \left(\frac{60}{i}\right)}{\sqrt{p} \text{ x (Instrument Eff.) x (Source Eff.)}}$$

The following subsections describe and give the rationale for selecting the inputs *d*', *p*, and *i*.

A.1.1.1. Index of Sensitivity

The audible detector response available to the surveyor can arise from either noise alone or from signal plus-noise and can be represented by two (typically overlapping) probability density distributions (Figure A.2). The task of the surveyor is to indicate whether an increase in survey instrument output arose from a "noise alone" or a "noise plus signal" event. To make this decision, a criterion must be established at some point along the continuum (e.g., once the criterion point is set, any measurement greater [to the right] than the criterion will be interpreted as contamination). If the underlying distributions can be assumed to be normal and of equal variance, an index of sensitivity (*d*') can be calculated that represents the distance between the means of the distributions in units of their common standard deviations. The index is calculated by transforming the true positive and false positive rates to standard deviation units (i.e., z-scores) and taking the difference:

d' = z (false positive) – z (true positive)

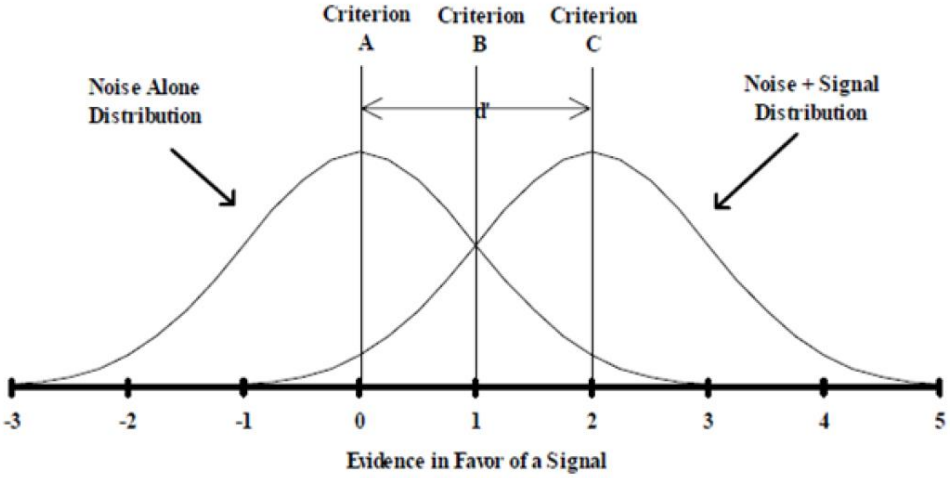

Figure A.2 *Signal Detection Theory Measures of Sensitivity (d') and Criterion Shown Relative to Assumed Underlying Distributions [NRC 2020]*

Table 6.5 of MARSSIM shows values of *d*' associated with various true positive and false positive rates [MARS 2002]. The *d*' measure is independent of the criterion adopted by the surveyor, thus allowing meaningful comparisons of sensitivity under conditions in which surveyors' criteria may be different.

Fermilab has approved a true positive rate of 95%, meaning that the ideal observer will identify contamination above the scan MDC 95% of the time. This also means there is a 5% probability of concluding that radiation levels are below the scan MDC when, in fact, radiation levels above the scan MDC are present.

There is also some probability that the surveyor will identify contamination when none is present. This may result in additional measurements, samples, or cleanup costs when none was required. Therefore, using guidance from DOE-STD-6004, Fermilab accepts a false positive rate of 30% [DOE 2016]. There is a 30% probability the ideal observer will incorrectly conclude that radiation levels are present above the scan MDC when they are not. With a true positive rate of 95 percent and a false positive rate of 30 percent, the materials release *d*' value is 2.16.

A.1.1.2 Surveyor Efficiency

A surveyor's performance can be related to that expected of an ideal observer by an efficiency factor (*p*), which represents the probability that an audible detector response above the scan MDC will be identified. NUREG/CR-6364 [NRC 1998] describes experiments demonstrating that (1) even under ideal circumstances, humans do not perform at 100-percent efficiency and (2) in scanning, where actual observation intervals may vary considerably without mechanical assistance, the efficiency of the surveyor (relative to the ideal observer) declines further. The factors that affect an individual's performance include, but are not limited to, survey technique, experience, the cost of false positive and false negative decision errors, and the expectation of the presence of radioactivity based on process knowledge.

Laboratory studies using simulated sources and backgrounds were performed to assess the abilities of surveyors under controlled conditions. The methodology and analysis of results for these studies are described in draft NUREG/CR-6364 and NUREG-1507 [NRC 2020]. The surveyor's actual performance as compared with that which is ideally possible provided an indication of the efficiency of the surveyors. Based on the results, this surveyor efficiency (*p*) is estimated to be between 0.5 and 0.75, but an efficiency value of 0.5 may be the more appropriate default for estimating field performance [MARS 2002].

A.1.1.3 Observation Interval

The observation interval (*i*) during scanning is the actual time that the detector can respond to the contamination source. It depends on the scan speed, detector orientation, and size of the detectable region. The detectable region relates to the area of detection defined by the detector-to-source geometry. The greater the areal extent of the contamination and the slower the scan rate, the greater the observation interval.

$$i = \frac{w}{s}$$

where:

i = observation interval (s)
w = width of detectable region (cm)
s = scan speed (cm/s)

In practice, surveyors do not make detection decisions based on a single indication. Rather, upon noting an increased number of counts, the surveyor will pause briefly and then decide whether to move on or take further measurements. Therefore, scanning consists of two components: continuous monitoring and stationary sampling. In the first stage, characterized by continuous movement of the probe, the surveyor may have only a brief "look" at potential radioactivity. The second stage occurs only after a positive response was made at the first stage. The surveyor interrupts their scanning and holds the probe stationary over the "source" while comparing the instrument output signal to the background count rate.

For conservatism, the greater value of MDCR is used to determine the scan sensitivity for the surveyor. Typically, the MDCR associated with the first scanning stage will be greater because of the brief observation intervals of continuous monitoring, provided that the length of the pause during the second stage is significantly longer.

A.2 Scan MDCs for Surface Radioactivity

The scan MDC for surface radioactivity is determined from the MDCR by applying conversion factors that account for surveyor, detector, and source efficiencies. The MDCR and surveyor efficiency are described above. The detector and source efficiencies are applied to the scan MDC calculation as follows:

$$\text{Scan MDC} = \frac{d'\sqrt{\left(\frac{R_b}{60}\right)i}\ \left(\frac{60}{i}\right)}{\sqrt{p}\ \text{x (Instrument Eff.) x (Source Eff.)}} = \frac{d'\sqrt{\left(\frac{R_b}{60}\right)i}\ \left(\frac{60}{i}\right)}{\sqrt{p}\ \varepsilon_i\ \varepsilon_s\ \left(\frac{PA}{100}\right)}$$

where:

ε_i = instrument efficiency
ε_s = source efficiency
PA = physical probe area of the radiation detector (cm^2)

The instrument efficiency (ε_i) is defined as the ratio between the net count rate of the instrument and the surface emission rate of a source for a specified geometry. The surface emission rate is the 2π particle fluence that embodies both the absorption and scattering processes that affect the radiation emitted from the source. Instrument efficiency (ε_i) is dependent on the detector size (probe surface area), window density thickness, geotropism, instrument response time, scan rate, and ambient conditions such as temperature, pressure, and humidity. Instrument efficiency also depends on solid angle effects, which include source to detector distance and source geometry.

The source efficiency (ε_s) is defined as the ratio between the number of particles of a given type above a given energy emerging from the front face of a source or its window per unit time (surface emission rate) and the number of particles of the same type created or released within the source (for a thin source) or its saturation layer thickness (for a thick source) per unit time [NRC 2020]. Source efficiency may be affected by source-related factors such as the type of radiation and its energy, source uniformity, surface roughness and coverings, and surface composition (e.g., metal, concrete). The source efficiency considers the increased particle emission resulting from backscatter effects, as well as the decreased particle emission because of self-absorption losses.

A.3 Scan MDCs for Volumetric Activation

Recalling the form of the generic scan MDC from A.1.1, the same MDCR and surveyor efficiency (*p*) discussed for surface contamination also apply here. However, methods for estimating the instrument and source efficiencies are significantly different when estimating scan MDCs for volumetric radioactivity (in pCi/g). These efficiencies relate to the areal extent and depth of the source, the source radionuclide(s) (i.e., energy and yield of gamma emissions), and the energy-dependent detector response to gamma radiation.

$$\text{Scan MDC} = \frac{d' \sqrt{\left(\frac{R_b}{60}\right) i} \ \left(\frac{60}{i}\right)}{\sqrt{p} \text{ x (Instrument Eff.) x (Source Eff.)}} = \frac{d' \sqrt{\left(\frac{R_b}{60}\right) i} \ \left(\frac{60}{i}\right)}{\sqrt{p} \text{ x CPMR x ERC}}$$

The instrument efficiency is defined as the count-rate-to-exposure-rate ratio (CPMR) and is determined by defining the relationship between the detector response and incident gamma energy (in units of cpm per µR/hr). Manufacturers typically provide an energy response curve or a single value on the curve for a given NaI detector, the preferred scintillation crystal used for volumetric radioactivity scanning surveys. In most cases, however, the CPMR is unknown and must be estimated.

The source efficiency is defined as the exposure-rate-to-concentration ratio (ERC) and is the measured or estimated exposure rate in µR/h at some distance from a source with a well-defined geometry (i.e., areal extent and depth). Programs like MARS and MicroShield must be used to model the chosen detector, material, volumetric radioactivity profile, proxy radionuclide and its yields/energies of gamma radiation to estimate the overall sensitivity or confirm those sensitivities determined by SLAC et. al.

A.4 Recommendations

Scan MDCs should be calculated using detector responses from areas that have not been contaminated by site activities. A release criterion that includes an MDCR should allow the surveyor to listen to the detector's audible response and identify anomalies in real time. The use of headphones for listening to the audio output enhances the surveyor's ability to distinguish signal from noise and, therefore, helps decrease the incidence of false negative decisions.

The following appendices will discuss the detection thresholds chosen by Fermilab to comply with DOE Order 458.1 and 5400.5 (surface contamination) and ANSI N13.12-2013 (volumetric radioactivity) for the unrestricted release of personal property.

Appendix B: Detection Thresholds for Volumetric Radioactivity

For volumetric radioactivity, DOE-STD-6004 prescribes 3-tiered clearance criteria related to ANSI N13.12-2013 volume SLs that may be used by DOE sites. Fermilab has chosen a criterion of radiologically indistinguishable from background (IFB) at a level lower than the volume SLs. Different measurement methods in different background levels can have different IFB levels. Therefore, each measurement method must have a detection threshold for proxy radionuclides less than the ANSI N13.12 volume SLs.

B.1 Surface Surveys

The critical level (L_C) is used as the detection threshold to identify an object as IFB. To produce a sufficiently low false positive rate, a confidence level of 99.95% has been chosen, corresponding to an *m* value of 3.291. If the sample and background counting times are equal, then at the 99.95% confidence level, L_C is defined as

$$L_C\ (\text{cpm}) = 4.65\sqrt{\frac{R_b}{t_b}}$$

Due to the presence of non-ideal effects (which are difficult to account for), the confidence level is likely closer to 99%. This 1% false positive rate is still lower than the typical 95% confidence level (5% false positives). Using this equation for the L_C produces a sufficiently low false positive rate even if there are some non-ideal effects taking place and has also been adopted by SLAC [SLAC 2011b] and referenced in DOE-STD-6004.

The ANSI N13.12 recommendations for the release criteria of volumetrically activated material are in terms of average activity per gram over a volume of interest. This is complicated because the L_C is only dependent on the detector used and the level of ambient background radiation—to measure a specific activity, additional variables must be considered: the counting geometry, the degree of volumetric activity profile and any self-shielding in the object under measurement. To ensure the L_C is less than the ANSI volume SL (i.e., the detector can measure below the specified limit), the L_C must be converted to units of activity by accounting for the instrument and source efficiencies. Therefore, the "critical concentration" (L_C in units of pCi/g) for fixed-position measurements is defined as

$$\text{Critical Concentration} = L_C\ (\text{pCi/g}) = \frac{4.65\sqrt{\frac{R_b}{t_b}}}{\text{CPMR x ERC}}$$

As determined from section A.3, the scan MDC for volumetric radioactivity is:

$$\text{Scan MDC} = \frac{d'\sqrt{\left(\frac{R_b}{60}\right)i}\ \left(\frac{60}{i}\right)}{\sqrt{p}\ \text{x CPMR x ERC}}$$

Fermilab uses a Bicron Analyst with a 1.5" diameter x 1" thick NaI(Tl) detector for measuring volumetric radioactivity. Because the instrument efficiency (CPMR) is energy dependent, it must be derived when the value is not known or if there is a mixture of gamma energies. The Bicron G1.5 model probe has a sensitivity of 320 cpm/µR/hr for ^{137}Cs [RPCF 2021]. This value, corrected for dead time and accepted by the manufacturer, will be used to determine CPMR values at gamma energies other than 662 keV.

The CPMR for a single gamma energy may be determined in four steps. These steps are described below for a 1.5" × 1" NaI detector and a 1275-keV gamma. Step 1 is to estimate the fluence rate for the specific energy of interest:

$$\text{Fluence Rate} = \frac{1\ \mu\text{R/h}}{E_\gamma(\mu_{en}/p)_{air}} = \frac{1}{(1275)(0.02651)} = 0.02959$$

where (μ_{en}/ρ) is the mass energy absorption coefficient for air and the value used is for 1275 keV [NIST 2004].

Step 2 is to estimate the probability of interaction within the detector's NaI crystal, assuming that the primary gamma interaction producing the detector response occurs through the end of the detector:

$$\text{P} = 1 - e^{-(\mu/p)_{NaI}(x)(\rho_{NaI})} = 1 - e^{-(0.0502)(2.54)(3.67)} = 0.374$$

where:

- $(\mu/\rho)_{NaI}$ is the mass absorption coefficient for NaI (0.0502 cm^2/g at 1275 keV) [Mannhart]
- x is the thickness of the NaI (2.54 cm)
- ρ_{NaI} is the density of NaI (3.67 g/cm^3)

Step 3 is to estimate the relative detector response, which is the product of the fluence rate and probability of interaction:

$$\text{Relative Response} = \text{Fluence Rate} \times \text{P} = 0.02959 \times 0.374 = 0.0111$$

Steps 1, 2, and 3 are repeated for the energy with the known CPMR value (in this case, 662 keV with a CPMR of 320 cpm/µR/h). The relative response for a 662-keV gamma is estimated to be 0.0262.

Finally, Step 4 is to estimate the energy-specific CPMR (for 1275 keV) by adjusting the known CPMR (for 662 keV) using calculated relative responses:

$$\text{CPMR}_{1275} = \text{CPMR}_{662}\ \text{x}\ \frac{\text{Relative Response}_{1275}}{\text{Relative Response}_{662}} = 320\ \text{x}\ \frac{0.0111}{0.0262} \approx 135\ \text{cpm/µR/hr}$$

A summary of the CPMR values for each gamma energy of interest is shown in Table B.1.

Table B.1 *Energy-specific CPMR values for proxy radionuclides*

Radionuclide	Energy (keV)	μ_{en}/ρ, Air (cm^2/g)	Fluence Rate	μ/ρ, NaI (cm^2/g)	P	Relative Response	CPMR (cpm/µR/hr)
Cs-137	662	0.02932	0.05152	0.0762	0.509	0.0262	320
Na-22	511	0.02967	0.06596	0.0925	0.578	0.0381	465
	1275	0.02651	0.02959	0.0502	0.374	0.0111	135
Co-60	1173	0.02703	0.03154	0.0530	0.390	0.0123	150
	1332	0.02623	0.02862	0.0494	0.369	0.0106	129

A weighted CPMR is required for mixed gamma fields, and this weighting involves using the source efficiency. Therefore, the exposure-rate-to-concentration ratio (ERC) is described first before calculating the weighted CPMR.

The source efficiency (ERC) depends on the material being surveyed (type, size, and shape), the potential volumetric radioactivity profile of the proxy radionuclide(s) inside the material, and the yields and energies of gamma radiation emitted by proxy radionuclide(s). To calculate the ERC, several factors must be considered:

- location of dose point (1 cm)
- concentration of the radionuclide of interest (1 pCi/g)
- energy emissions from the radionuclide of interest
- density of material
- areal dimensions of hotspot
- depth of hotspot

Volumetric activation geometry was modeled by SLAC in MCNP [2011a] for a Co-60 source distributed in a piece of iron. It was found that the detector sees at least 80% of the total yield in the first 6 cm and to a radius of 20 cm when the source is distributed uniformly in the iron, at 1 cm from the surface on the central axis of the cylinder. This volume was set as the "detectable region," a region from which gamma rays can be detected by the detector (which depends on material type and gamma ray energy). Additional simulations were performed using Na-22 in aluminum, with a detectable region 4-cm thick with a 15-cm radius (representing small samples), and Co-60 in copper, with a detectable region 2-cm thick with a 15-cm radius (representing thin samples).

Fermilab used the model shown in Figure B.1 to perform confirmatory simulations using both the MARS Monte Carlo code [MCNP 2018] and MicroShield [MCSD 2021]. An additional simulation was performed using Na-22 in concrete, with a detectable region 6-cm thick with a 20-cm radius. Uniform source distribution was assumed because this results in the lowest sensitivity and therefore is a conservative choice if the actual radioactivity profile is unknown.

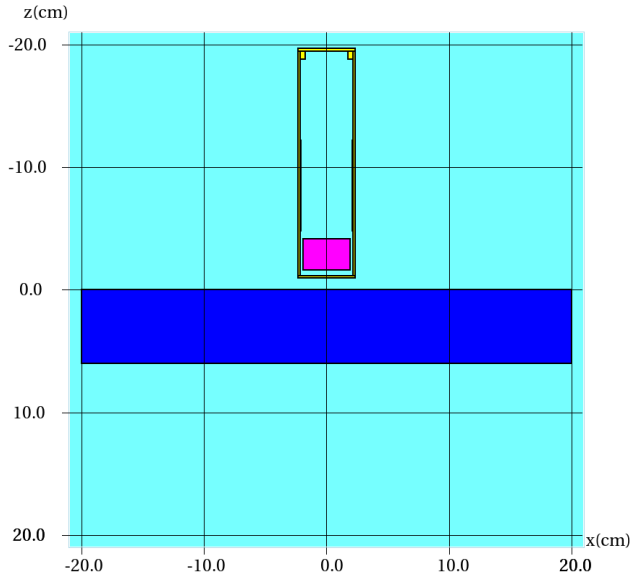

Figure B.1 *MARS model of 1.5" x 1" NaI(Tl) detector*

Although the resulting gamma energy spectrum incident on the NaI detector (both primary and scattered gamma radiation) must be accounted for, the MicroShield modeling code considered only primary gamma energies when evaluating the buildup from scattered photons. The NaI detector response will be greater than the calculated detector response during field applications because the detector is more efficient at detecting lower energy scattered photons. The results using MicroShield are expected to yield a conservative determination of the detector response and resulting detection threshold.

Because ^{22}Na and ^{60}Co both produce a mixed gamma radiation field, the CPMR and ERC are evaluated concurrently. MicroShield provided the exposure rates for the gamma energies associated with these proxy radionuclides. Using the energy-specific CPMR values in Table B.1, the energy-specific ERC values (MicroShield output) are used to weight the energy-specific CPMR values. The total ERC and the total weighted CPMR are then compiled as follows:

$$\text{Weighted CPMR}_j \text{ (cpm/µR/hr)} = \frac{ERC_j \text{ x } CPMR_j}{\sum ERC_j}$$

The detection thresholds for the Bicron Analyst may now be calculated for given values of the L_C and MDCR and the efficiency terms *p*, *CPMR,* and *ERC* for various gamma energies. Results of these calculations are tabulated in Tables B.2 through B.4.

The detection thresholds for both fixed-position measurements and scan surveys for volumetric radioactivity are below the ANSI N13.12-2013 Group 1 limit for proxy radionuclides, 3 pCi/g.

Table B.2 *Weighted energy-specific CPMR values for proxy radionuclides*

		^{22}Na in Aluminum		**^{22}Na in Concrete**		**^{60}Co in Copper**		**^{60}Co in Iron**	
Energy (keV)	$CPMR_j$ (cpm per µR/hr)	ERC_j (µR/hr per pCi/g)	Weighted $CPMR_j$ (cpm per µR/hr)	ERC_j (µR/hr per pCi/g)	Weighted $CPMR_j$ (cpm per µR/hr)	ERC_j (µR/hr per pCi/g)	Weighted $CPMR_j$ (cpm per µR/hr)	ERC_j (µR/hr per pCi/g)	Weighted $CPMR_j$ (cpm per µR/hr)
511	465	0.4714	208	0.5620	206	—	—	—	—
1275	135	0.5807	75	0.7102	75	—	—	—	—
1173	150	—	—	—	—	0.7781	71	1.088	70
1332	129	—	—	—	—	0.8763	68	1.244	69
TOTALS		**1.0521**	**283**	**1.2722**	**281**	**1.6544**	**139**	**2.332**	**139**

Table B.3 *Critical level and critical concentration for volumetric radioactivity measurement methods using a Bicron Analyst with 1.5" diameter x 1" thick NaI(Tl) detector*

Parameter	Description	^{60}Co in iron	^{22}Na in concrete	^{60}Co in copper	^{22}Na in Aluminum
R_b	Background count rate (cpm)	3000			
t_b , t_{s+b}	Background, sample count time (min)	1			
Critical Level	Detection Threshold for fixed-position measurements (cpm)	**254**			
Weighted CPMR	Instrument efficiency (cpm/µR/hr)	139	281	139	283
ERC	Source efficiency (µR/hr/pCi/g)	2.332	1.2722	1.6544	1.0521
Critical Concentration	Detection Threshold for fixed-position measurements (pCi/g)	**0.79**	**0.71**	**1.11**	**0.86**

Table B.4 *Scan MDC for volumetric radioactivity measurement methods using a Bicron Analyst with 1.5" diameter x 1" thick NaI(Tl) detector*

Parameter	Description	^{60}Co in iron	^{22}Na in concrete	^{60}Co in copper	^{22}Na in Aluminum
R_b	Maximum background count rate (cpm)	3000	3000	3000	3000
d'	Index of sensitivity	2.16	2.16	2.16	2.16
w	width of detectable region (cm)	40	40	30	30
s	Scan speed (cm/s)	5.08	5.08	5.08	5.08
i	Observation interval (s)	8	8	6	6
p	Surveyor efficiency	0.5	0.5	0.5	0.5
Weighted CPMR	Instrument efficiency (cpm/µR/hr)	139	281	139	283
ERC	Source efficiency (µR/hr/pCi/g)	2.332	1.2722	1.6544	1.0521
Scan MDC	Detection Threshold for volumetric radioactivity scan surveys (pCi/g)	**1.41**	**1.28**	**2.30**	**1.78**

B.2 Confirmatory Measurements

To supplement surface surveys, confirmatory measurements may be performed to validate the surface measurements for volumetric radioactivity. These include field gamma spectrometry over the object's surface, collection of representative samples for Fermilab or external radioanalytical laboratory analysis using environmental measurement protocols, and/or the use of a portal gate monitor.

B.2.1 Field Gamma Spectrometry and Laboratory HPGe

The minimum detectable concentration (MDC), derived from the L_D, should be used for the portable and laboratory detectors as the detection threshold for IFB [SLAC 2011b]. When surveying an item for release, if the net count rate is less than the detection threshold, the item under measurement is classified as IFB. However, when the number of counts is small, the Poisson statistical model begins to break down. The result is an inaccurate measure of the standard deviation of the background used to determine whether the number of counts is statistically significant. If the L_C is used to determine whether an object is IFB, then the result is a large number of false positives due to the inaccurate use of the Poisson model. If the L_D is selected, the number of false positives is greatly reduced. While this method is not strictly IFB, it is a tradeoff between a large reduction in false positive rate and a small decrease in the sensitivity of the detection system.

Field gamma spectrometry measurements utilize a portable gamma spectrometer to identify the potential existence of gamma-emitting radionuclides above the spectrometer's MDC. Fermilab uses the Ortec GammaVision analysis software combined with an Ortec HPGe detector for field gamma spectrometry measurements. The MDC for field gamma spectrometry measurements is less than 1 pCi/g for proxy radionuclides for typical counting geometries [RAF 308].

The laboratory sample measurements involve collecting one or more representative samples for low-background HPGe gamma spectrometry. Currently, the RAF at Fermilab is equipped with four (4) HPGe spectrometers, with one (1) HPGe system designated for the measurement of environmental samples. The MDC of this system is less than 0.1 pCi/g for proxy radionuclides for a standard counting geometry.

The state-of-the-art field gamma spectrometers and laboratory instruments have lower detection thresholds than field survey meters. These limits apply to environmental samples, where the expectation is to have environmental levels of radioactivity (i.e., little to no radioactivity present). The field gamma spectrometers and laboratory instruments can be used as benchmark or confirmatory measurements for field surveys when warranted, at the expense of higher operating cost and time.

B.2.2 Portal Gate Monitor

The Fermilab portal gate monitor is a Ludlum Model 4525-14000. The system has four (4) scintillation detectors, each 3500 in^3 for a total of 14,000 in^3. Each detector utilizes two (2) PMTs, which is an increase in efficiency of 30% over one PMT. These cover a large area to address the potential mass effect (i.e., many components with low radioactivity level in each component can collectively generate a larger radiation signal than an individual component). The system's typical detection capability is about 1 µCi of ^{60}Co (as a point source), or in the range of 0.1-1 pCi/g for proxy radionuclides with a uniform volumetric radioactivity per truckload or individual large-volume container [DOE 2016]. Vehicles transporting cleared impacted scrap metal (or other bulk items) should exit the site via the Ludlum 4525-14000 vehicle gate monitor. For small containers (e.g., drums), a survey of the exterior of the package using a Bicron Analyst in rate-meter mode is sufficient.

Appendix C: Detection Thresholds for Surface Radioactivity

For surface radioactivity, DOE Order 458.1 allows the use of the surface contamination guidelines given in DOE Order 5400.5 Figure IV-1 as the pre-approved Authorized Limits for unrestricted release of personal property that may be potentially surface contaminated. DOE Order 5400.5 Figure IV-1 does not have surface contamination guidelines for tritium. Appendix D to 10 CFR 835 sets a removable surface contamination value of 10,000 dpm/100 cm^2 for tritium, which DOE guidance recommends as an acceptable limit for unrestricted release. Property may be released if the results of a survey with appropriate instruments indicate that the potential activity of the property is less than the surface contamination guidelines given in DOE Order 5400.5 Figure IV-1 and 10 CFR 835.

C.1 Surface Surveys

As determined from section A.2, the scan MDC for surface radioactivity is:

$$\text{Scan MDC} = \frac{d'\sqrt{\left(\frac{R_b}{60}\right) i}\ \left(\frac{60}{i}\right)}{\sqrt{p}\ \varepsilon_i\ \varepsilon_s\ \left(\frac{PA}{100}\right)}$$

From a conservative point of view, it is better to overestimate the MDC for a measurement method. Therefore, when calculating the MDC, a measurement system background value has been selected that represents the high end of what is expected for a particular measurement method, as well as realistic values of detection efficiencies and other process parameters that reflect actual conditions.

In accordance with MARSSIM, the instrument efficiency (ε_i) used for the MDC calculations is the 2π instrument efficiency [MARS 2002]. Fermilab primarily uses two instruments to measure surface radioactivity: a Ludlum 177-4 and Eberline 140N, both with Ludlum 44-9 GM pancake detectors. Ludlum provides several 4π efficiencies for the 44-9 GM detector [LDLM 2018]. These 4π efficiencies and their corresponding radionuclide, as well as the type and energy of radiation emitted from each radionuclide, are listed in Table C.1.

Fixed contamination proxy radionuclides include ^{60}Co and ^{22}Na. ^{60}Co emits a beta minus particle at 317 keV, while ^{22}Na emits a higher energy positron at 546 keV. The radionuclide that most closely matches these decay energies is ^{99}Tc. This is a conservative option, as both ^{60}Co and ^{22}Na emit beta particles at higher energies than the 297.5 keV beta minus particle emitted by ^{99}Tc.

To estimate the 2π instrument efficiency, the 4π instrument efficiency is multiplied by two (2). The 4π efficiency for the 44-9 for ^{99}Tc is 19%. Therefore, the 2π instrument efficiencies (ε_i) for both the Ludlum 177-4 and Eberline E140N are estimated to be 38%.

Table C.1 *Ludlum Model 44-9 Alpha-Beta-Gamma Detector 4π Efficiencies*

Radionuclide	Emission (keV)	Efficiency (4π)
^{14}C	β^- : 156.475	5%
^{99}Tc	β^- : 297.5	19%
^{90}Sr/^{90}Y	β^- : 545.9/2278.5	22%
^{32}P	β^- : 1710.66	32%

The 2π instrument efficiencies account for the detector size (probe surface area), window density thickness, and solid angle effects, but do not consider non-uniform contamination or rough surfaces that may offer significant self-attenuation. Therefore, a source efficiency (ε_s) must be selected that accounts for the type of radiation and its energy, source uniformity, surface roughness and coverings, and surface composition (e.g., metal, concrete). The source efficiency considers the increased particle emission resulting from backscatter effects, as well as the decreased particle emission because of self-absorption losses.

Source efficiencies have been selected from the guidance in MARSSIM [MARS 2002]:

- ε_s = 0.5 for beta-emitters ($E_{\beta max}$ > 0.4 MeV)
- ε_s = 0.25 for beta-emitters (0.15 MeV < $E_{\beta max}$ < 0.4 MeV)

^{99}Tc emits a beta minus particle at 0.2975 MeV, so a source efficiency of 0.25 was chosen. This value is also the more conservative option and overestimates the MDC, particularly for smoother metal surfaces; a source efficiency of 0.25 better applies to M&E with rough surfaces (i.e., concrete). The scan MDC and terms used to calculate the scan MDC for both surface radioactivity instruments are presented in Table C.2.

Table C.2 *Scan MDC calculations for surface radioactivity measurements*

Parameter	Description	Ludlum 177-4 with 44-9 detector		Eberline 140N with 44-9 detector	
		Value	Units	Value	Units
R_b	Maximum background count rate	80	cpm	50	cpm
d'	Index of sensitivity	2.16	–	2.16	–
w	Width of probe face	5.08	cm	5.08	cm
s	Scan speed	1	cm/s	1	cm/s
i	Observation interval	5	seconds	5	seconds
p	Surveyor efficiency	0.5	–	0.5	–
ε_i	Instrument efficiency (2π)	0.38	cpm/dpm	0.38	cpm/dpm
ε_s	Source efficiency	0.25	–	0.25	–
PA	Probe area	20.3	cm^2	20.3	cm^2
Scan MDC	Detection Threshold for surface radioactivity scan surveys	4877 dpm/100 cm^2		3855 dpm/100 cm^2	

In addition to scanning the surface of an item, a static count must be performed every 1 m^2 at each potentially elevated area or in a representative area if no elevated reading is detected during the scan survey. The MDC, derived from the L_D, should be used for static measurements of potentially surface-contaminated items. As determined from Appendix A.1, the L_D is defined as:

$$L_D\ (\text{cpm}) = \frac{m^2}{t_{s+b}} + 2\,m\sqrt{\frac{R_b}{t_b}\left(1 + \frac{t_b}{t_{s+b}}\right)}$$

To determine the MDC, the L_D must be converted into units of activity by incorporating the instrument and source efficiencies:

$$\text{Static MDC} = L_D\ (\text{dpm}/100\ \text{cm}^2) = \frac{\frac{m^2}{t_{s+b}} + 2\,m\sqrt{\frac{R_b}{t_b}\left(1 + \frac{t_b}{t_{s+b}}\right)}}{\varepsilon_i\ \varepsilon_s\ \left(\frac{\text{PA}}{100}\right)}$$

To produce a 95% confidence level, an *m* value of 1.645 has been chosen. As the instruments used for static measurements are the same as those used for scan surveys, the same efficiencies and probe area may be used. Table C.3 summarizes the static MDCs for direct measurements using a Ludlum 177-4 and Eberline 140N with a 44-9 pancake GM detector.

The total contamination limit from DOE Order 5400.5 Figure IV-1 is 5000 dpm/100 cm^2. Although fixed contamination is quite rare at Fermilab, performing scan and static surveys with a pancake GM detector is a viable option, as each instrument can achieve sensitivity that satisfies the surface contamination limits in Figure IV-1 of DOE Order 5400.5.

Table C.3 *Static MDC calculations for surface radioactivity measurements*

Parameter	Description	Ludlum 177-4 with 44-9 detector		Eberline 140N with 44-9 detector	
		Value	Units	Value	Units
m	Constant associated with the selected confidence level	1.645	–	1.645	–
R_b	Maximum background count rate	80	cpm	50	cpm
t_b	Time to count the background	1	min	1	min
t_{s+b}	Time to count the sample	1	min	1	min
ε_i	Instrument efficiency (2π)	0.38	cpm/dpm	0.38	cpm/dpm
ε_s	Source efficiency	0.25	–	0.25	–
PA	Probe area	20.3	cm^2	20.3	cm^2
Static MDC	Detection Threshold for surface radioactivity fixed-position surveys	2161 dpm/100 cm^2		1709 dpm/100 cm^2	

C.2 Removable Contamination Measurements

When the presence of removable contamination is known or suspected, additional radiological measurements must be performed. The measurement method chosen depends on the radionuclide(s) present and includes laboratory analysis of representative samples of the item using a gas-flow proportional counter, liquid scintillation counter (LSC), or HPGe spectrometry.

C.2.1 Gas-Flow Proportional Counter (Proxy Radionuclides)

Like confirmatory measurements of volumetric radioactivity, the MDC, derived from the L_D, should be used for measurements with the gas-flow proportional counter. As determined from Appendix A.1, the L_D is defined as:

$$L_D\ (\text{cpm}) = \frac{m^2}{t_{s+b}} + 2\,m\sqrt{\frac{R_b}{t_b}\left(1 + \frac{t_b}{t_{s+b}}\right)}$$

To determine the MDC, the L_D must be converted into units of activity by incorporating the instrument efficiency. Per Fermilab's RP Note 96 [RAF 2012], a mixed wipe efficiency ($\varepsilon_{i,\,mixed}$) is used as the beta/gamma efficiency of a proportional counter system.

$$\text{Static MDC} = L_D\ (\text{dpm}/100\ \text{cm}^2) = \frac{\frac{m^2}{t_{s+b}} + 2\,m\sqrt{\frac{R_b}{t_b}\left(1 + \frac{t_b}{t_{s+b}}\right)}}{\varepsilon_{i,mixed}}$$

To calculate the beta/gamma efficiency of a proportional counter system for a 'typical' wipe, the following equations are used:

$$\text{Eff}_{\text{steel}} = \frac{\left(\text{Eff}_{^{54}\text{Mn}}\ \text{x}\ 10\right) + \left(\text{Eff}_{^{60}\text{Co}}\ \text{x}\ 1\right)}{11}$$

$$\text{Eff}_{\text{aluminum}} = \text{Eff}_{^{22}\text{Na}}$$

$$\text{Eff}_{\text{concrete}} = \text{Eff}_{^{22}\text{Na}}$$

$$\varepsilon_{i,mixed} = \frac{\text{Eff}_{\text{steel}} + \text{Eff}_{\text{aluminum}} + \text{Eff}_{\text{concrete}}}{3}$$

Using the above equations, Table C.4 summarizes the detection threshold for counting surface swipes/smears on a gas-flow proportional counter.

The removable contamination limit from DOE Order 5400.5 Figure IV-1 is 1000 dpm/100 cm^2. Therefore, with the parameters shown in Table C.4, the gas-flow proportional counter can achieve sensitivity that satisfies the surface contamination limits in Figure IV-1 of DOE Order 5400.5.

Table C.4 *Static MDC calculations for surface radioactivity measurements with gas-flow proportional counter located at RAF*

Parameter	Description	Value
m	Constant associated with the selected confidence level	1.645
R_b	Maximum background count rate (cpm)	3
t_b	Time to count the background (min)	10
t_{s+b}	Time to count the sample (min)	1
$\varepsilon_{i,\ Na\text{-}22}$	Instrument efficiency (2π), Na-22	0.23
$\varepsilon_{i,\ Co\text{-}60}$	Instrument efficiency (2π), Co-60	0.18
$\varepsilon_{i,\ Mn\text{-}54}$	Instrument efficiency (2π), Mn-54	0.03
$\varepsilon_{i,\ mixed}$	Instrument efficiency (2π), mixed wipe	0.17
Static MDC	Detection Threshold for surface swipes/smears (GFP)	52 dpm/100 cm^2

C.2.2 Liquid Scintillation Counter (LSC) measurements

Liquid scintillation counting is primarily used for tritium measurements using environmental counting protocols. The RAF at Fermilab is equipped with two (2) LSC systems for the measurements of environmental samples, as well as surface swipes for ^3H in concrete. Laboratory samples are prepared by swiping external surfaces of the item and placing them in LSC vials for analysis of ^3H. The MDC for LSC measurements using environmental counting protocols is less than 10 dpm/100 cm^2 for ^3H in concrete [RAF 303].

C.2.3 Beryllium-7

A survey for ^7Be must be done in any area with a large air gap in the primary beam, and any location where the particle flux is high enough to create significant spallation in air with comparatively low air flow, including:

1. The Main Injector abort face, the MTA/ITA air gap and target box, and inside the MTA abort cave
2. High loss areas such as collimators that, depending on the energy of the beam, are mainly contained to the beam pipe
3. Beam pipes where there are losses due to missteering of the beam or continued operation of the beam with a magnet failure
4. Absorber blocks in the MI12 decay pipe

Swipes that must be evaluated for ^7Be contamination are sent to the RAF and analyzed by one or more of the following methods.

C.2.3.1 HPGe Gamma Spectrometry

Like confirmatory measurements of volumetric radioactivity, the MDC, derived from the L_D, should be used for gamma spectrometry measurements. As determined from Appendix A.1, the L_D is defined as:

$$L_D\ (\text{cpm}) = \frac{m^2}{t_{s+b}} + 2\,m\sqrt{\frac{R_b}{t_b}\left(1 + \frac{t_b}{t_{s+b}}\right)}$$

To determine the MDC for ^{7}Be, the L_D must be converted into units of activity by incorporating the full-energy peak efficiency for ^{7}Be ($\varepsilon_{FP,\ Be\text{-}7}$).

$$\text{Static MDC} = L_D\ (\text{dpm}/100\ \text{cm}^2) = \frac{\frac{m^2}{t_{s+b}} + 2\,m\sqrt{\frac{R_b}{t_b}\left(1 + \frac{t_b}{t_{s+b}}\right)}}{\varepsilon_{FP,Be-7}}$$

The full-energy peak efficiency of ^{7}Be on an HPGe detector is the product of the detector efficiency at 477.6 keV ($\varepsilon_{i,\ Be\text{-}7}$) and the geometric efficiency or solid angle involved ($\varepsilon_{SA,\ Be\text{-}7}$):

$$\varepsilon_{FP,Be-7} = \left(\varepsilon_{i,Be-7}\right) x\ \left(\varepsilon_{SA,Be-7}\right)$$

Because the background count rate (R_b) around the 477.6 keV peak varies greatly depending on how active the sample is, the MDC for ^{7}Be also varies and is calculated each time ^{7}Be is analyzed and reported. The largest window on the detector with the highest background provides the maximum value for R_b. The ^{7}Be peaks are no more than 5 keV wide at the base (475 – 480 keV). At this window, the highest value for R_b on the detector with the highest background is 387 cpm [RAF 2022]. Conversely, the lowest detector and geometric efficiencies are used to determine the conservative value for the MDC.

Using the above values and equations, Table C.5 summarizes the detection threshold for counting ^{7}Be swipes/smears on Fermilab's HPGe gamma detector(s). The removable contamination limit from DOE Order 5400.5 Figure IV-1 is 1000 dpm/100 cm^2. Therefore, with the parameters shown in Table C.5, HPGe Gamma Spectrometry can achieve ^{7}Be sensitivity that satisfies the surface contamination limits in Figure IV-1 of DOE Order 5400.5.

Table C.5 *Static MDC calculations for ^{7}Be surface radioactivity measurements with HPGe Gamma Spectrometry located at RAF*

Parameter	Description	Value
m	Constant associated with the selected confidence level	1.645
R_b	Maximum background count rate (cpm)	387
t_b	Time to count the background (min)	1440
t_{s+b}	Time to count the sample (min)	60
$\varepsilon_{i,\ Be\text{-}7}$	Instrument efficiency (2π) at 477.6 keV[1,2,3,4]	0.182
$\varepsilon_{SA,\ Be\text{-}7}$	Geometric efficiency/solid angle of HPGe measurement[1,2,3]	0.0675
$\varepsilon_{FP,\ Be\text{-}7}$	Full-energy peak efficiency, Be-7	0.01227
Static MDC	Detection Threshold for Be-7 (HPGe)	699 dpm/100 cm^2

[1] Assumes the sample is a regular cloth swipe/smear with a diameter of 4.5 cm
[2] Assumes the active area of the sample completely covers the swipe and also has a diameter or 4.5 cm
[3] Assumes the counting distance of the sample is nominally 4 cm from the active face of the crystal, minus 0.08 cm standard wipe-in-glassine-envelope thickness
[4] Assumes there is no self-absorption of 477.6 keV gammas taking place

C.2.3.2 Gas-Flow Proportional Counter

To determine the MDC for ^{7}Be, the same equations and approach from section C.2.1 are used. The instrument efficiency, however, is no longer for a 'typical' wipe with a mixture of proxy radionuclides—the efficiency is strictly for ^{7}Be, a radionuclide that emits a 477.6 keV gamma (E_γ) at a 10.44% branching ratio ($Y_{477.6}$). To estimate the efficiency for this hard-to-measure radionuclide, the known efficiency for a similar radionuclide (i.e., type and energy of radiation emitted) may be used as a starting point. ^{54}Mn emits a gamma ray at 834.8 keV and has a measured efficiency of 3%. Therefore, the ^{7}Be efficiency can be estimated as follows:

$$\text{Eff}_{^{7}\text{Be}} = \frac{\text{Eff}_{^{54}\text{Mn}}}{\left(\frac{E_{\gamma,^{54}\text{Mn}}}{E_{\gamma,^{7}\text{Be}}}\right)} \text{ x } Y_{477.6} = \frac{0.03}{\left(\frac{834.8}{477.6}\right)} \text{ x } 0.1044 \approx 0.0018$$

Using the above ^{7}Be efficiency and longer background and sample counting times, Table C.6 summarizes the detection threshold for counting ^{7}Be swipes/smears on a gas-flow proportional counter.

The removable contamination limit from DOE Order 5400.5 Figure IV-1 is 1000 dpm/100 cm^2. Therefore, with the parameters shown in Table C.6, the gas-flow proportional counter may achieve ^{7}Be sensitivity that satisfies the surface contamination limits in Figure IV-1 of DOE Order 5400.5.

Table C.6 *Static MDC calculations for ^{7}Be surface radioactivity measurements with gas-flow proportional counter located at RAF*

Parameter	Description	Value
m	Constant associated with the selected confidence level	1.645
R_b	Maximum background count rate (cpm)	3
t_b	Time to count the background (min)	60
t_{s+b}	Time to count the sample (min)	60
$\varepsilon_{i,\ Be\text{-}7}$	Instrument efficiency (2π), Be-7	0.0018
Static MDC	Detection Threshold for Be-7 (GFP)	603 dpm/100 cm^2

C.2.3.3 *Reserved*

Appendix D: ANSI N13.12 Screening Level Groups for Uncharacterized Radionuclides

Screening level groups for clearance were established in ANSI N13.12, *Surface and Volume Radioactivity Standards for Clearance*, for over 130 radionuclides and selected decay chains; however, not all radionuclides determined to be a significant contribution to the modeled radioactivity for concrete and carbon steel in Fermilab's source term were included. Using the recommended methodology described in ANSI N13.12, these additional radionuclides were grouped by comparing their NCRP screening factors, by exposure scenario, listed in Tables B.1, C.1, and D.1 of NCRP Report No. 123I. The screening factors are for scenarios that consider releases to the atmosphere, fresh surface water, and ground. Comparison radionuclides were selected that are similar in decay mode, chemical properties, and half-life to the additional radionuclides, as feasible. The decay characteristics of the additional radionuclides are listed in Appendix Table D.1. The screening factors for the additional radionuclides and the comparison radionuclides were obtained from Tables B.1 through D.1 of NCRP Report No. 123I [NCRP 1996] for each scenario, as shown in Table D.2.

Table D.1 *Additional Radionuclides not included in Table 1 of ANSI N13.12-2013*

Radionuclide	Half Life (d)	Decay Mode	Similar Mode of Decay from Table 1 Groups	Comments
^{37}Ar	35	Electron Capture (EC), γ	3, 4, 5	
^{39}Ar	9.8E4	β^-	3, 4, 5	
^{41}Ca	3.7E7	EC, γ	2, 3, 4, 5	
^{55}Co	0.7	β^+, γ	1, 2, 3	
^{64}Cu	0.5	β^+/EC/ β^-, γ	2, 3, 4	
^{52}Mn	5.6	β^+/EC, γ	1, 2, 3	
^{56}Mn	0.1	β^-, γ	1, 2, 3	
^{44}Ti/^{44}Sc	2.3E4 / 0.16	EC, β^+, γ	1, 2, 3	In equilibrium
^{48}V	16.0	β^+/EC, γ	1, 2, 3, 4	
^{49}V	330	EC	2, 3, 4, 5	

Table D.2 *NCRP Report No. 123I Screening Factors*

Radionuclide	Half Life *(d)*	Decay Mode	ANSI Screening Level Group	Table B.1 Screening Factor *(Sv / Bq m^{-3})*	Table C.1 Screening Factor *(Sv / Bq m^{-3})*	Table D.1 Screening Factor *(Sv / Bq)*
^{37}Ar	35	EC, γ	Not Listed	1.7E-12	2.3E-16	Not Listed
^{39}Ar	9.8E4	β^-	Not Listed	Not Listed	1.6E-13	Not Listed
^{41}Ca	3.7E7	EC, γ	Not Listed	2.4E-03	1.0E-08	6.4E-13
^{55}Co	0.7	β^+/EC, γ	Not Listed	7.50E-05	1.60E-09	2.00E-18
^{64}Cu	0.5	β^+/EC/ β^-, γ	Not Listed	5.2E-06	1.5E-10	Not Listed
^{52}Mn	5.6	β^+/EC, γ	Not Listed	9.6E-04	2.9E-08	Not Listed
^{56}Mn	0.1	β^-, γ	Not Listed	9.1E-06	6.1E-10	Not Listed
^{44}Ti/^{44}Sc	2.3E4/0.16	EC, β^+, γ	Not Listed	4.5E-01	1.4E-05	2.9E-11
^{48}V	16.0	β^+/EC, γ	Not Listed	2.8E-03	1.4E-08	7.4E-27
^{49}V	330	EC	Not Listed	2.3E-05	1.5E-10	5.4E-15
^{22}Na	9.5E2	β^+, γ	1	1.0E-01	3.2E-07	1.4E-12
^{54}Mn	3.1E2	EC, γ	1	9.7E-03	3.4E-07	3.8E-15
^{46}Sc	83.8	β^-, γ	1	6.6E-03	2.1E-07	8.9E-18
^{58}Co	70.9	EC, β^+, γ	2	4.2E-03	1.8E-08	6.9E-18
^{59}Fe	44.5	β^-, γ	2	4.3E-03	7.4E-08	4.8E-20
^{109}Cd	4.6E2	EC, γ	2	2.8E-03	1.5E-08	2.8E-14
^{74}As	17.8	EC, β^+, γ	3	1.4E-03	8.6E-09	6.7E-28
^{103}Ru	39	β^-, γ	3	1.1E-03	2.1E-09	1.4E-20
^{7}Be	53.1	EC, γ	3	1.2E-04	4.6E-10	4.1E-21
^{45}Ca	1.6E2	β^-	4	1.0E-03	1.7E-08	4.2E-15
^{86}Rb	18.6	β^-, γ	4	4.8E-03	5.0E-08	1.1E-26
^{51}Cr	27.7	EC, γ	4	9.2E-05	3.7E-10	3.7E-24
^{73}As	80.3	EC, γ	5	3.1E-04	2.3E-09	2.4E-18
^{55}Fe	1.0E3	EC, γ	5	2.8E-04	1.5E-09	9.9E-16
^{89}Sr	50.5	β^-, γ	5	3.6E-03	1.3E-08	4.1E-18

The screening factor values from Table D.2 for the additional uncharacterized radionuclides were compared to radionuclides from groups with similar modes of decay. The screening factors that most closely matched those of the additional radionuclides were used to assign a clearance screening level group for each uncharacterized radionuclide, as summarized in Table D.3. In cases where the radionuclides with the most closely matching screening factors from the NCRP scenarios are assigned to different ANSI screening level groups, the radionuclide was assigned to the lowest (i.e., most restrictive) clearance screening level group shown.

Table D.3 *Clearance screening level group determination for the additional radionuclides considered*

Radionuclide	Most Closely Matching Screening Levels and (clearance screening level group)			Assigned Group
	Table B.1	Table C.1	Table D.1	
^{37}Ar	^{51}Cr (4)	^{51}Cr (4)	N/A	4
^{39}Ar	N/A	^{51}Cr (4)	N/A	4
^{41}Ca	^{109}Cd (2)	^{89}Sr (5)	^{109}Cd (2)	2
^{55}Co	^{7}Be (3)	^{103}Ru (3)	^{58}Co (2)	2
^{64}Cu	^{51}Cr (4)	^{51}Cr (4)	N/A	4
^{52}Mn	^{103}Ru (3)	^{58}Co (2)	N/A	2
^{56}Mn	^{51}Cr (4)	^{7}Be (3)	N/A	3
^{44}Ti/^{44}Sc	^{22}Na (1)	^{54}Mn (1)	^{22}Na (1)	1
^{48}V	^{109}Cd (2)	^{109}Cd (2)	^{74}As (3)	2
^{49}V	^{51}Cr (4)	^{45}Ca (4)	^{45}Ca (4)	4

The short-lived proxies ^{52}Mn and ^{56}Mn do not necessarily dominate the dose risk as longer-lived proxy radionuclides do because they may not be classified as Group 1 per ANSI N13.12. The gammas emitted by these radionuclides are comparable to those emitted by the long-lived Group 1 radionuclides designated as proxies under longer irradiation and decay times in DOE-STD-6004-2016 (e.g., ^{22}Na, ^{54}Mn, ^{60}Co). Therefore, they will have similar detection sensitivities of less than 3 pCi/g using the volumetric scanning techniques described in section 5.3.3.2 and can ensure that the IFB approach will be sufficiently protective.