RADIATION PHYSICS NOTE 124

TECHNICAL BASIS FOR EXTERNAL DOSIMETRY AT FERMILAB

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Revision History

Author	Description of Change	Revision Date
K. Graden & M. Vincent	Revision 13 Updated to include LBNF-FS; modified neutron accreditation	March 2022
S. McGimpsey	Revision 12 Incorporated training program to include admin/technical support and new Dosimetry Program Manager	July 2018
S. McGimpsey	Revision 11 Updated to reflect dosimeter changes	March 2018
S. McGimpsey	Revision 10 Incorporated Fermilab operational and organizational changes	June 2015
S. McGimpsey	Revision 9 Incorporated Fermilab operational changes; editorial changes	June 2012
S. McGimpsey	Revision 8 Incorporated Fermilab operational changes	December 2011
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S. McGimpsey	Revision 6 Updated to reflect changes to 10 CFR 835	June 2010
S. McGimpsey	Revision 5 Adherence to revision schedule	June 2009
S. McGimpsey	Revision 4 Adherence to revision schedule	June 2006
S. McGimpsey	Revision 3 Editorial changes	November 2003
S. McGimpsey	Revision 2 Incorporated Fermilab operational changes	November 2000
D. Boehnlein	Revision 1 Editorial changes	September 1998
D. Boehnlein	Revision 0	August 1996

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1.0 Acronyms

ANL	Argonne National Laboratory
ANSI	American National Standards Institute
BODA	Beam-On Dose Assessment
CMTF	Cryomodule Test Facility
CFR	Code of Federal Regulations
DOE	Department of Energy
DOELAP	Department of Energy Laboratory Accreditation Program
DU	Depleted Uranium
DUNE	Deep Underground Neutrino Experiment
ES&H	Environment, Safety and Health
eV	Electron Volt
FNAL	Fermi National Accelerator Laboratory (Fermilab)
FRCM	Fermilab Radiological Control Manual
ILC	International Linear Collider
LBNF	Long-Baseline Neutrino Facility
LBNF-FS	Long-Baseline Neutrino Facility Far Site
LDR	Landauer
Linac	Linear Accelerator
LLD	Lower Limit of Detection
mR	milliRoentgen
NIST	National Institute of Standards and Technology
OSL	Optically Stimulated Luminescence
PIP	Proton Improvement Plan
PD	Pocket Dosimeter
RF	Radiofrequency
SURF	Sanford Underground Research Facility
TBM	Technical Basis Manual
TLD	Thermoluminescent Dosimeter

2.0 Purpose

This Technical Basis Manual (TBM) provides a methodology for establishing and operating an External Dosimetry Program at Fermilab that will comply with the Department of Energy (DOE) requirements specified in Title 10 of the Code of Federal Regulations Part 835, Occupational Radiation Protection [1]. For completeness, this document also identifies applicable recommendations contained in DOE-STD-1095-2018 (*Department of Energy Laboratory Accreditation Program for External Dosimetry*) [2], DOE-STD-1098-2008 (*DOE Radiological Control Standard*) [3], DOE G 441.1-1C Chg 1 (*Radiation Protection Programs Guide for Use with 10 CFR 835, Occupational Radiation Protection*), the *Fermilab Radiological Control Manual* (FRCM) [4], and secondary documents such as American National Standards Institute (ANSI) standards invoked by these primary documents.

3.0 Introduction to Fermilab

Located in Batavia, IL and Lead, SD and funded by the U.S. Department of Energy, Fermi National Accelerator Laboratory (FNAL) is America's premier laboratory for particle physics and accelerator research. Thousands of scientists around the world collaborate with Fermilab on research at the frontiers of discovery. Its mission is to solve the mysteries of matter, energy, space and time for the benefit of all by striving to lead the world in neutrino science with particle accelerators, to lead the nation in the development of particle colliders and their use for scientific discovery, and to advance particle physics through measurements of the cosmos. Fermilab drives discovery by building and operating world-leading accelerator and detector facilities, performing pioneering research with national and global partners, and developing new technologies for science that support U.S. industrial competitiveness.

At Fermilab's main campus in Batavia, a system of particle accelerators provides high-energy particle beams for the conduct of various experiments in particle physics. These presently consist of several major neutrino experiments, the Muon g-2 experiment, a 120 GeV fixed target program, and several smaller test experiments. The laboratory is currently working on the construction of major new neutrino and muon physics experiments as well as significant upgrades to current accelerators to continue to support the intensity frontier.

The Proton Improvement Plan II (PIP-II) project currently under construction will replace Fermilab's aging 400 MeV Linear Accelerator (Linac) with a state-of-the-art superconducting radiofrequency (RF) linear accelerator capable of accelerating high-intensity beam up to 1 GeV before transferring it into the existing accelerator system. PIP-II will enable the laboratory to advance its plans for new large-scale projects such as the Long-Baseline Neutrino Facility (LBNF) and the Mu2e experiment, which will further our understanding of fundamental physics.

The LBNF project will provide the new beamline and civil construction for the Deep Underground Neutrino Experiment (DUNE), an international experiment for neutrino science and proton decay studies. DUNE requires the construction and operation of a massive Far Detector situated 1.5 km below ground at the Sanford Underground Research Facility (SURF) in Lead, South Dakota, as well as a separate Near Detector located on-site at Fermilab. The DUNE-related areas and facilities at SURF are under Fermilab's direct management and are collectively referred to as the LBNF Far Site (LBNF-FS). Unlike at the Batavia site, no particle accelerators will be located at the LBNF Far Site.

At Fermilab in Batavia, extensive research and development is also performed on superconducting RF cavities. This work involves building the necessary infrastructure to fabricate, process, treat, and test superconducting RF cavities for future accelerators of many types. RF cavity testing facilities include Vertical Test Stands in the Industrial Building complex as well as the Cryomodule Test Facility (CMTF), which houses two stands for testing cryomodules of different frequencies in pulsed or continuous wave mode.

Both in Lead and in Batavia, Fermilab also operates power, water, ventilation, cryogenic cooling, cyberinfrastructure, and various other systems necessary to ensure the safety of personnel and accelerator and experimental equipment.

At the Batavia site, radiological work is conducted in the radiation fields produced by the accelerators as well as with materials radioactivated by the accelerated beams. Most radiological work in Batavia involves maintenance and repairs on accelerator components that have been radioactivated by the particle beam. Preparation of radioactive waste for disposal is also performed.

At both the Batavia and Lead locations, sealed radioactive sources and neutron generators are utilized for calibration purposes and as important components of the particle detectors. Radioactive materials are sometimes incorporated into experimental apparatus and beamline components.

Work with all of the sources of radiation mentioned above is a part of routine operations at Fermilab. The personnel who conduct such work must be monitored for exposure to ionizing radiation in accordance with 10 CFR 835.

4.0 Overview of Fermilab's External Dosimetry Program

Fermilab's External Dosimetry Program is designed and conducted to evaluate the equivalent dose to an individual in order to:

- Demonstrate compliance with the dose limits of 10 CFR 835 and the FRCM
- Document radiological conditions in the workplace
- Detect changes in radiological conditions
- Provide required data for reporting doses to individuals and federal agencies
- Detect the gradual buildup of radioactive material in the workplace
- Verify the effectiveness of engineering and process controls in containing radioactive material and reducing radiation exposure
- Identify and control potential sources of individual exposure to radiation and/or radioactive material

The Environment, Safety, and Health Section (ES&H) at Fermilab has the overall responsibility of implementing the External Dosimetry Program. This program provides monitoring and recording of external radiation exposure for all personnel working at Fermilab in compliance with 10 CFR 835. Within ES&H, the Radiation Physics Science department has the responsibility to ensure that all activities associated with the dosimetry program are maintained in compliance with the Department of Energy Laboratory Accreditation Program (DOELAP). An organization chart can be found in the *External Dosimetry Quality Program Manual* [5].

Fermilab's External Dosimetry Program utilizes dosimeters supplied and processed by a commercial vendor. The program provides whole-body monitoring and extremity monitoring and is DOELAP accredited. For DOELAP accreditation, vendor dosimeters used at Fermilab must have passed DOELAP performance testing. Fermilab as well as the vendor undergo separate onsite DOELAP assessments, providing assurance that the administration of the External Dosimetry Program is in conformance with DOELAP requirements. DOELAP accreditation is on a three-year cycle.

Radiological workers at Fermilab are monitored for external exposure on a quarterly basis, although fetal monitors are exchanged on a monthly basis. Dosimeters are collected and sent to the vendor for processing. The dose reports are then sent to Fermilab; once the reported doses have been verified and approved, they become the external radiation doses of record. Fermilab's dosimetry vendor is the official repository for all external radiation doses of record; copies of dose reports are retained at Fermilab for reference.

5.0 Implementation

This section provides basic guidance for conducting Fermilab's External Dosimetry Program for workers who are likely to receive external exposure to ionizing radiation. Conducting an External Dosimetry Program involves determining monitoring methods, frequency, distribution and control, and evaluating external dose from monitoring results. This section also includes guidance for conducting workplace monitoring of external radiation, and for recording, reporting, and managing external doses. Organization, staffing, and training as well as the requirement for this Technical Basis Manual are also addressed in this section.

The essential elements of an External Dosimetry Program are as follows:

- Adequate staff shall be maintained and shall be provided with appropriate technical training
- Complete historical records of personnel dosimeter measurement results and dose assessments shall be maintained
- An internal audit program shall be conducted annually and structured in a way that ensures all elements of DOE-STD-1095-2018 are reviewed over the three-year accreditation period
- Adequate equipment shall be acquired and maintained sufficient to meet the needs of the External Dosimetry Program at Fermilab
- Management shall ensure adequate resources are provided to fully implement the External Dosimetry Program

In addition, an External Dosimetry Program should contain the following elements:

- Written policies and procedures covering each step in the activities that determine worker external dose
- Appropriate personnel dosimeter measurement methods and frequencies
- Adequate detection capability and quality of personnel dosimeter measurements
- Appropriate dose models and default parameters for evaluating external dose
- Methods for control, accountability, and safe handling of dosimeters
- Appropriate action level and investigation level guidelines
- Timely analysis of personnel dosimeter measurements, transmission of results, dose evaluation, and recommendations to management
- Historical records of the External Dosimetry Program and its procedures
- Quality assurance program covering all steps in the activities that determine worker external dose
- Criteria for identifying individuals who need to be monitored for exposure to external sources of radiation
- A method for reporting external doses to workers, management, and DOE
- Access to radiation survey data to support planning and scheduling of dosimetry practices, to provide the means to identify and investigate unusual exposures and radiological events, and to correct dose measurements where appropriate

6.0 DOELAP Categories

10 CFR 835 mandates that Fermilab maintain DOELAP accreditation. DOELAP specifies a number of irradiation categories for the performance of whole-body dosimeters:

I. Accident Photons
   A. General (B and C, random)
   B. ^{137}Cs
   C. M150

II. Photons/Photon Mixtures
   A. General (Avg. E ≥ 20 keV; $\perp$ if ≤ 70 keV)
   B. High E (^{137}Cs, ^{60}Co; $\alpha \leq 60°$)
   C. Medium E (Avg. E > 70 keV, $\alpha \leq 60°$)
   D. Plutonium Specific

III. Betas
   A. General (B and C, random)
   B. High E (^{90}Sr/^{90}Y)
   C. Low E (^{85}Kr)
   D. Uranium Slab

IV. Photon/Beta Mixtures

V. Neutron/Photon Mixtures
   A. General (B and C, random)
   B. ^{252}Cf + II
   C. ^{252}Cf (D_2O) + II

These categories are described in detail in the relevant ANSI standard [6].

Fermilab currently maintains accreditation in the following categories: IA, IIA, IIIA, IIID, IVA-1 (IIA + IIIA mixture), IVD-1 (IIA + IIID mixture), and VB-1 (IIA + Bare Neutrons). With the upcoming introduction of neutron generator use at Fermilab and at the LBNF Far Site, category VA will be added to Fermilab's DOELAP accreditation, replacing category VB. Accreditation in the other categories is not necessary. Fermilab does not have any sources of plutonium.

DOELAP also specifies a number of irradiation categories for the performance of extremity dosimeters:

I. High-Dose Photons
  A. General (B and C, random)
  B. 137Cs (Avg. E = 0.662 keV)
  C. M150 (Avg. E = 73 keV)

II. Photons
  A. General (Avg. E ≥ 20 keV)
  B. High Energy (Avg. E ≥ 500 keV)
  C. Medium Energy (Avg. E ≥ 70 keV)
  D. Narrow Spectrum

III. Betas
  A. General (B and C, random)
  B. High Energy Point Source (Avg. E ≥ 500 keV)
  C. Low Energy Point Source (Avg. E < 500 keV)
  D. Slab Uranium (Avg. E ≥ 500 keV)

IV. Beta/Photon Mixtures
  A. General Photon + Beta
  B. Gamma + Beta

These categories are described in detail in the relevant ANSI standard [7].

Fermilab currently maintains accreditation in the following extremity categories: IA, IIA, IIIA, and IIID.

7.0 Photon Radiation

Photon radiation at Fermilab, which presents the major occupational exposure concern, is primarily due to work with activated items including beamline components, shielding materials, experimental apparatus, etc. The radionuclides typically found in such items are mainly ^{22}Na, ^{54}Mn, and ^{60}Co. A variety of other radionuclides are also produced in smaller quantities. These isotopes primarily emit gamma radiation with energies between 0.5 MeV and 1.5 MeV.

The accelerators at Fermilab are also capable of producing low energy photons/X-rays. For example, the linear accelerator (Linac), radiofrequency (RF) systems, and Vertical Test Stands may emit low energy photons in the energy range of 20 keV to 180 keV. As a result, accreditation in DOELAP categories IA and IIA is appropriate. These categories use ^{137}Cs, ^{60}Co and NIST X-ray techniques, which are comparable to the aforementioned photon fields.

Fermilab has a number of sealed sources for instrument calibration and experimental use. Work with these sources mostly involves ^{60}Co, ^{137}Cs, and ^{22}Na. Some instrument check sources such as ^{55}Fe are also in use at Fermilab, but the 6 keV X-ray from ^{55}Fe decay is below the energy range addressed by DOELAP and is not considered an external radiation hazard (see Appendix A).

8.0 *Beta Radiation*

Beta radiation is produced by beta/gamma-emitting activation products at Fermilab as previously described. However, beta radiation is less of a concern than gamma because, with few exceptions, radioactive materials at Fermilab are produced by volume activation of materials. Since the radionuclides are distributed throughout the depth of the activated item, rather than being concentrated on the surface, most of the beta radiation is absorbed within the material. Occasional surface contamination involving beta emitters is possible; however, these areas are generally very small and well controlled. The most common and exceptionally long-lived activation product of potential concern at Fermilab is ^{60}Co; this isotope emits beta particles, the vast majority of which have an energy of about 0.32 MeV.

Beta-emitting sealed radioactive sources are used at Fermilab, most commonly ^{90}Sr and ^{106}Ru.

To account for the above sources of beta radiation, accreditation in DOELAP category IIIA has been chosen. The sources used for the category are ^{90}Sr/^{90}Y and ^{85}Kr.

Fermilab has an inventory of depleted uranium (DU), most of which is enclosed within the decommissioned DZero calorimeter and related devices and is inaccessible under normal circumstances. Disassembly or modification of the DZero detector may eventually be necessary, and therefore Fermilab continues to maintain accreditation in category IIID (uranium slab).

9.0 *Neutrons*

Neutrons are produced at Fermilab under beam-on conditions by the interaction of the beam with beamline components, targets, or beam absorbers. At their point of production, the neutrons may have extremely high energies, almost at the primary beam energy. Such high-energy neutrons are produced only in exclusion areas where no personnel would be present during beam-on conditions. Some of the neutrons, however, may filter out through labyrinths, penetrations, or shielding, producing neutron fields in areas where personnel may be exposed. Another potential source of neutron exposure at Fermilab is the use of encapsulated neutron sources, such as ^{241}Am-Be or ^{252}Cf.

Outside of well-shielded high-energy accelerator facilities, the radiation weighting factor of the radiation field is approximately that of an Am-Be radiation field (see Table 6.6 in Reference [8]). Consequently, Am-Be is the best reference for testing and calibration of personnel dosimeters. (DOELAP tests fast neutron response using a bare Cf spectrum, which is somewhat softer, i.e. biased towards lower energies, than Am-Be. [9])

Neutron generators are neutron source devices that contain compact linear accelerators and produce neutrons by fusing isotopes of hydrogen. These fusion reactions take place by accelerating either deuterium, tritium, or a mixture of these two isotopes into a metal hydride target that also contains deuterium, tritium, or a mixture of them.

Deuterium-Deuterium (D-D) neutron generators fuse deuterium atoms, resulting in the formation of a He-3 ion and a neutron with a kinetic energy of approximately 2.5 MeV. Deuterium-Tritium neutron generators fuse deuterium and tritium atoms, resulting in the formation of a He-4 ion and a neutron with a kinetic energy of approximately 14.1 MeV. Neutron generators in use at Fermilab and at the LBNF Far Site will have a range of energies from 0.5 MeV up to 14.1 MeV.

Due to the variety of potential neutron sources described above, category VA is considered to be the appropriate category for Fermilab DOELAP accreditation.

10.0 Dosimeters

10.1 Whole-Body Dosimeters

The dosimeter of record currently in use to monitor the types of radiation potentially encountered at Fermilab is the Landauer (LDR) InLight Model 2T, which combines a beta/gamma detector element with a CR-39 neutron detector. The beta/gamma detector element is a layer of aluminum oxide crystals, Al_2O_3, sandwiched between two layers of polyester. This is used with a set of filter materials (plastic, aluminum, and copper), which are capable of differentiating between beta and various photon energies. The equivalent dose is assessed to the whole body at a depth of 1 cm in tissue, to the lens of the eye at 0.3 cm depth, and to the skin and extremities at 0.007 cm depth.

Optically Stimulated Luminescence (OSL) [10] is the method of analysis applied to the beta/gamma detector. OSL is similar to Thermoluminescent Dosimeters (TLDs); however, instead of using heat to release radiation-excited electrons back to lower energy states, OSL uses light of a specific wavelength. Use of OSL material provides many advantages including very little fading over time, imperviousness to environmental factors (temperature, pressure, etc.), and re-read capabilities. A vendor algorithm is used to isolate the response for each type of radiation (beta and gamma). The algorithm applies correction factors based on the isolated responses to arrive at the absorbed dose for the whole body, the lens of the eye, and the skin for each type of radiation measured. Additional details on the specifications and capabilities of the InLight Model 2T can be found in the *External Dosimetry Quality Program Manual*. The response of this dosimeter is linear from 1 mrem to in excess of 100 rem. Fermilab has selected a minimum reportable dose of 10 mrem per monitoring period.

Track-etch dosimetry, where a material records the tracks of recoil protons from fast neutron scattering, is one of the most effective technologies for neutron detection [11]. Industry studies have indicated that allyl diglycol carbonate (trade name CR-39) is the material most sensitive to higher-energy neutrons. The addition of boron-loaded Teflon over one half of the CR-39, as in the InLight Model 2T, allows for thermal, intermediate, and fast neutron measurement. CR-39 neutron tracks are revealed using a well-controlled chemical etching process. This, together with a careful readout process, yields a neutron detection energy threshold of 40 keV. A dose algorithm developed at Landauer is used to convert tracks per mm^2 to equivalent dose to the whole body. The minimum reportable fast neutron dose is 10 mrem per monitoring period. The adequacy of track-etch detectors for neutron dosimetry at Fermilab has been established by studies of neutron fields at Fermilab and by the demonstrated sensitivity of CR-39 to higher-energy neutron fields both in published literature [11] and as verified by blind audit results.

The InLight Model 2T dosimeter is DOELAP accredited in the following categories: IA, IIA, IID, IIIA, IIID, IVA, IVD, VA, and VB. Additional information regarding InLight Model 2T specifications such as lower limit of detection (LLD) and angular response studies can be found in the Dosimetry Program Office.

10.2 Extremity Dosimeters

Fermilab uses the Landauer Saturn Ring badge for measuring radiation dose to the extremities. This dosimeter consists of a single ^{nat}LiF (TLD-100) chip. For processing these dosimeters, Landauer uses a Preco Laser-Heated TLD System. The lithium fluoride element is heated by a laser, causing luminescence in proportion to the amount of radiation exposure.

The ability of TLDs like the Saturn Ring to detect the types of radiation found at Fermilab is well-established [12]. Fermilab used TLDs for whole-body monitoring for many years before transitioning to the InLight LDR Model 2T Dosimeter.

The Saturn Ring dosimeter is DOELAP accredited in extremity categories IA, IIA, IID, IIIA, and IIID. Additional information regarding its specifications, LLD, and angular response can be found in the Dosimetry Program Office.

11.0 Supplemental Dosimeters

In addition to a primary dosimeter, supplemental dosimetry is sometimes used to obtain an immediate reading of an integrated dose. Obtaining an instantaneous dose measurement instead of waiting for a badge to be processed serves three basic purposes:

1. The wearer can determine if a significantly large dose has been received during the badge wear period so that work may be planned for the remainder of the wear period to keep doses As Low as Reasonably Achievable (ALARA).

2. An unexpected dose might indicate the presence of an unanticipated radiation hazard or the need for a revised work procedure.

3. If a primary dosimeter should be lost, a supplemental dosimeter provides some data to help complete an exposure investigation.

The pocket ionization chamber, also known at Fermilab as a pocket dosimeter (PD), is a small ion chambers with a visual readout. They are an industry standard and are well-suited to the role of supplemental dosimeter.

Pocket dosimeters are sensitive primarily to gamma radiation, which is the major dosimetry concern at Fermilab. Although these dosimeters are relatively insensitive to neutrons, Fermilab almost never has neutron-only radiation fields, but rather has mixed radiation fields. In nearly all cases, where there are neutrons, there will also be gamma radiation, so the PD is able to serve adequately in a supplemental role. The PD is also insensitive to beta radiation, but, as described previously, beta exposures are not the paramount concern at Fermilab.

Electronic dosimeters are also occasionally used to monitor exposures, primarily in High Radiation Areas during beam-off conditions. These are small Geiger counters that are primarily sensitive to gamma radiation. They have an LED readout displaying the exposure in milliRoentgen (mR) and can be configured to audibly alarm either once per mR or thirty to forty times per mR.

12.0 Accident Dosimetry

Accident dosimetry is usually applied to nuclear criticality accidents; these conditions do not exist at Fermilab. The characteristic accident at Fermilab that would result in a large dose is a direct beam-on exposure. In such an incident, most of the dose would come from high-energy hadrons; however, a high-energy particle beam will activate any matter upon which it is incident, including the human body, with the amount of induced radioactivity being dependent on the dose received.

If an individual were to suffer a beam-on exposure, the procedure for dose reconstruction is through the use of a whole-body-counting apparatus. A dose would be estimated based on the radioactivity induced in the body [13]. The whole body-counter at Fermilab is suitable only for making a preliminary estimate of the dose and cannot be used to assign dose to an individual. This equipment and its related procedures are located at the Beam-On Dose Assessment (BODA) Facility at the Site 39 South Annex.

A more detailed assessment could be made using the whole-body counting facilities at Argonne National Laboratory (ANL). Fermilab maintains a contract with ANL for whole body counting services should the need ever arise for it.

13.0 Supporting Documentation

Additional supporting documentation is maintained in the *Technical Basis Manual* binder in the Dosimetry Program Office and in the ES&H Document Database. This documentation includes qualification and training records, blind audit results [14], and DOELAP performance testing [15] and accreditation documents [16]. All operating procedures can be found in the *External Dosimetry Procedures Manual.* Quality assurance information can be found in the *External Dosimetry Quality Program Manual.*

14.0 References

1. 10 C.F.R. § 835

2. Department of Energy Laboratory Accreditation Program for Personnel Dosimetry
   DOE-STD-1095-2018, U.S. Department of Energy, October 2018

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13. Dose Estimates at the Beam-On Dose Assessment Facility, C. Salsbury and A. Elwyn, Fermilab RP Note 85, ESH-doc-2200, April 1990

14. External Dosimetry Program Blind Audit Results, ESH-doc-6882

15. DOELAP Performance Test Results for Landauer Dosimeters, ESH-doc-6714, August 2021

16. DOELAP Accreditation Documents 2018, ESH-doc-4825, January 2019

Appendix A: ^{55}Fe Radioactive Sources At Fermilab

Fermilab typically maintains an inventory of ^{55}Fe radioactive sources ranging in activity from a few microCuries to several milliCuries. The 6 keV X-ray emitted by this nuclide borders the sensitivity limit of the LDR InLight Model 2T dosimeters. The question considered here is whether or not Fermilab's personnel dosimetry needs to be sensitive to the radiation emitted from ^{55}Fe radioactive sources. The X-ray is of such low energy that it does not pose a whole-body hazard, therefore only the skin dose is considered here. From *The Health Physics and Radiological Health Handbook* (B. Shleien, 1992), the flux to equivalent dose rate for photons in the energy range from 10 - 30 keV is given by

$$\ln D(E) = -20.477 - 1.7454 \ln E \qquad \text{(rem/hr)(cm}^2\text{ s)} \qquad \text{(A.1)},$$

where E is the photon energy in MeV. The constants, taken from Table 6.1.1 of the above reference, represent the lowest energy range for which the numbers are available, which are still somewhat higher than the 6 keV of ^{55}Fe.

Solving the above for D,

$$D(6\ \text{keV}) = 3.73\ (\mu\text{rem / hr})(\text{cm}^2\ \text{s}) \qquad \text{(A.2)}.$$

Assume that one rem equivalent dose to the skin (2% of the allowed regulatory annual limit) is the lowest dose of concern, and that one hour is a typical time spent working in close proximity to the source. Equation (A.2) may be used to determine what flux F of ^{55}Fe photons would produce a shallow equivalent dose of one rem:

$$F = \left(3.73 \times 10^{-6}\right)^{-1} = 2.68 \times 10^{5}\ (\text{s}^{-1}\ \text{cm}^{-2}) \qquad \text{(A.3)}.$$

Assume next that the source (approximately a point source) is 30 cm away from the trunk of the body of a Standard Man, which has an area S of 3240 cm^2. The rate at which photons which must impinge on the trunk of the body to deliver an equivalent dose of one rem in one hour is:

$$N = FS = 8.68 \times 10^{8}\ \text{s}^{-1} \qquad \text{(A.4)}$$

One must consider here the attenuation of 6 keV photons in air. Referring again to Shleien for the attenuation coefficient, a simple calculation shows that a beam of 6 keV photons is reduced to 43.6% of its original intensity after passing through 30 cm of air. Clothing further attenuates the 6 keV photons.

Again using numbers from Shleien and assuming a 0.05 cm layer of nylon approximates the effect of a shirt, the radiation is reduced to 54.8% of what penetrates the 30 cm of air. This attenuation introduces a correction factor c.

Thus, the activity of a source delivering a one rem equivalent dose is:

$$A = N\frac{Sc}{4\pi r^2} = \frac{8.68\times10^8}{(0.436)(0.524)}\frac{3240\,\mathrm{cm}^2}{4\pi(30\,\mathrm{cm})^2} = 1.09\times10^8\ \mathrm{Bq} \qquad \text{(A.5).}$$
$$= 29.4\,\mathrm{mCi}$$

This activity is a more than an order of magnitude higher than any ^{55}Fe source in Fermilab's inventory.

Note that this calculation is based on a very conservative estimate of the solid angle, since at a distance of 30 cm, the body would not approximate a spherical surface very well, and the geometry would actually make the body a smaller target than is indicated here. Even with these assumptions, however, it is seen that the ^{55}Fe sources in Fermilab's inventory will not deliver significant doses. There is, therefore, no need for concern that the sensitivity of the InLight Model 2T dosimeter is close to the energy of the ^{55}Fe.