CHAPTER 8 ACCELERATOR SHIELDING AND RADIOACTIVATION

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Radiological control performance is affected by human performance and engineered design features. This Chapter sets forth the policies for the design of new facilities and major modifications to existing facilities. The Appendix to this chapter contains a synopsis and abbreviated bibliography of references on shielding design methodology.

For purposes of this chapter, "dose" means effective dose as defined by ICRP Publications 60, 61, 74, and 103. Likewise, the terms "quality factor" Q and "effective quality factor" Q_{eff} are considered to be equivalent to "radiation weighting factor w_R addressed in ICRP Publications 60, 61, 74, and 103.

PART 1 POLICIES AND PROCEDURES CONCERNING SHIELDING OF ACCELERATORS/BEAMLINES

811 Policy on Design Criteria

1. The following is the Fermilab policy on shielding design:

    a. Dose rates in areas of continuous occupancy shall be less than an average of 0.05mrem/hr and as far below this as is reasonably achievable (see Articles 234 and 236). Dose rates for potential exposure to radiological workers in areas without continuous occupancy shall be ALARA and such that individuals do not receive more than 20% of the applicable limits as stated in Table 2-1.

    b. Discharges of radioactive liquid to the environment are covered by provisions of DOE Order 5400.5 (Chapter 2 Section 1, and Chapter 3 in the Order) and the concentrations should be kept as far below the groundwater discharge limit as possible.

    c. Contamination should be controlled by providing containment of radioactive material that has the potential for generating removable contamination.

    d. Efficiency of maintenance, decontamination, operations, and decommissioning should be maximized.

    e. Materials and components should be selected to minimize the radiological concerns, both occupational and environmental.

    f. Provisions should be made for donning and removal of protective clothing and for personnel monitoring, when appropriate.

    g. Criteria for the conduct and review of shielding assessments are set forth in this chapter.

h. Internal exposure should be avoided by the use of engineered controls such as ventilation, containment, and filtration systems, where practicable (see Article 316).

i. Dose to members of the public from all DOE airborne emissions sources should be maintained as low as reasonably achievable (see also Chapter 11).

2. Temporary conditions involving facilities under construction including parking lots should be evaluated and the above criteria applied where practicable. Deviations from these criteria for such transient conditions shall be approved by the SRSO.

3. Locating eating areas, office space, rest rooms, drinking fountains, showers and similar facilities and devices within radiological areas is strongly discouraged. Unless office space is essential to support radiological work, steps should be taken to preclude unnecessary occupancy.

4. The design of facilities where neutron radiation is anticipated should use a quality factor of 20 unless measurements or calculations can demonstrate that a different quality factor more adequately describes the radiation field. The radiation weighting factors for neutrons to be used are those given in ICRP Publication 103 and reproduced *verbatim* in Tables 8-1 and 8-2 and illustrated in Fig. 8-1.

5. New or modified accelerator/beamline facilities shall have a shielding assessment performed, as specified in Article 812. (Many reference documents have been generated over the years at Fermilab and elsewhere that describe accelerator shielding design and radioactivation. These may be incorporated by reference in the accelerator/beamline shielding assessments.)

6. Results of shielding assessments conducted using methodologies established prior to the amendments to 10 CFR 835 issued in June 2007 remain valid in view of the analysis of (Co09a). Shielding assessments conducted after January 1, 2010 shall employ updated methodologies based upon ICRP Publication 103.

7. For purposes of this article, a modification to shielding which requires a shielding assessment under Article 812 is one that has the potential to permanently change the level of personnel protection provided by radiation shielding as defined in Article 236. Such modifications include those which result in a permanent change to the personnel access status of an area or those which result in modification of the “official” as-built drawings (see Article 812).

8. Division/section/center ES&H personnel shall be intimately involved in all stages of the process, from the conceptual stage through operations. All final designs, including construction packages ready for bid must be reviewed and approved by

the division/section/center management, the Division/Section/Center RSO, and the SRSO.

9. The Appendix to this chapter gives a summary and short bibliography on the design of accelerator radiation shielding.

The radiation weighting or quality factors specified in ICRP Publication 103 to be used for determining equivalent dose in rem without supplementary information about the details of the radiation field are provide in Table 8-1.

Table 8-1 Radiation Weighting or Quality Factors

Radiation Type	**Radiation Weighting or Quality Factor**
Photons	1
Electrons and muons	1
Protons and charged pions	2
Alpha particles, fission fragments, heavy ions	20
Neutrons	A continuous function of neutron energy, see See Table 8-2 and Figure 8-2.

If the knowledge of the neutron energy spectrum is insufficient to identify the energy of the neutrons, a quality or radiation weighting factor of 20 shall be used. The results of Ref. (Co09a) listed in the appendix to this chapter provide typical neutron energy spectra generated by the accelerators at Fermilab, with appropriate radiation weighting factors that may be used to support shielding assessments.

Table 8-2 Neutron Radiation Weighting or Quality Factors According to ICRP Publication 103

E_n (MeV)	w_R	E_n (MeV)	w_R	E_n (MeV)	w_R
1.0×10^{-9}	2.50	0.20	14.3	30	6.04
1.0×10^{-8}	2.50	0.30	16.8	40	5.69
2.5×10^{-8}	2.50	0.50	19.3	50	5.50
1.0×10^{-7}	2.50	0.70	20.3	60	5.36
2.0×10^{-7}	2.50	0.90	20.7	75	5.16
5.0×10^{-7}	2.50	1.0	20.7	100	4.86
1.0×10^{-6}	2.50	1.2	20.0	130	4.57
2.0×10^{-6}	2.50	1.5	18.9	150	4.40
5.0×10^{-6}	2.50	2.0	17.3	180	4.20
1.0×10^{-5}	2.50	2.5	16.0	200	4.08
2.0×10^{-5}	2.50	3.0	15.0	300	3.66
5.0×10^{-5}	2.50	4.0	13.3	400	3.40
1.0×10^{-4}	2.50	5.0	12.0	500	3.23
2.0×10^{-4}	2.50	6.0	11.1	700	3.01
5.0×10^{-4}	2.50	7.0	10.3	1.0×10^{3}	2.84
1.0×10^{-3}	2.51	8.0	9.72	1.5×10^{3}	2.70
2.0×10^{-3}	2.53	9.0	9.22	2.0×10^{3}	2.63
5.0×10^{-3}	2.67	10	8.81	3.0×10^{3}	2.57
1.0×10^{-2}	3.03	12	8.16	5.0×10^{3}	2.53
2.0×10^{-2}	3.92	14	7.67	1.0×10^{4}	2.51
3.0×10^{-2}	4.84	15	7.47	2.0×10^{4}	2.50
5.0×10^{-2}	6.58	16	7.30	5.0×10^{4}	2.50
7.0×10^{-2}	8.10	17	7.14	1.0×10^{5}	2.50
0.10	10.0	18	7.00	1.0×10^{6}	2.50
0.15	12.5	20	6.76	1.0×10^{7}	2.50

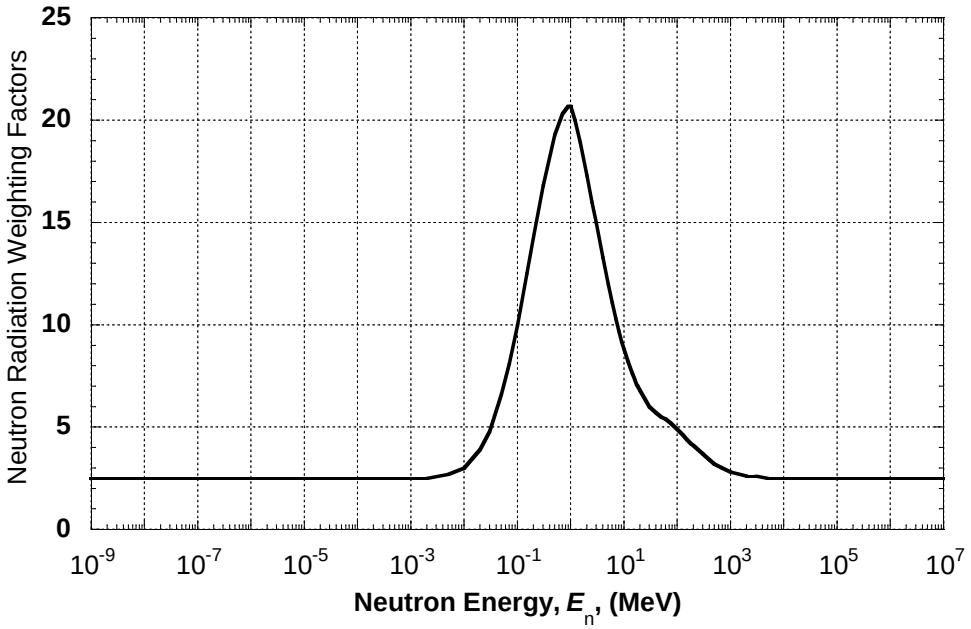

***Figure 8-1 Neutron Radiation Weighting (Quality) Factors as a function of neutron energy.* (*Based on ICRP Publication 103.*)**

812 Responsibilities for Configuration Control of Radiation Shielding

It is imperative to design new and modified accelerator facilities at Fermilab in a way that provides adequate shielding against prompt radiation fields and, to the extent practicable, residual radioactivation. Adequate protection of the environment as discussed in other FRCM and FESHM Chapters is also required before a given facility is constructed or modified both to assure safe operation and fiscal economy. The accelerator safety assessment policy set forth in FESHM 2010 is part of this integrated approach. The responsibilities span multiple organizations as described in this Article. The flowchart shown in Fig. 8-2 describes the specifics of the shielding design review process.

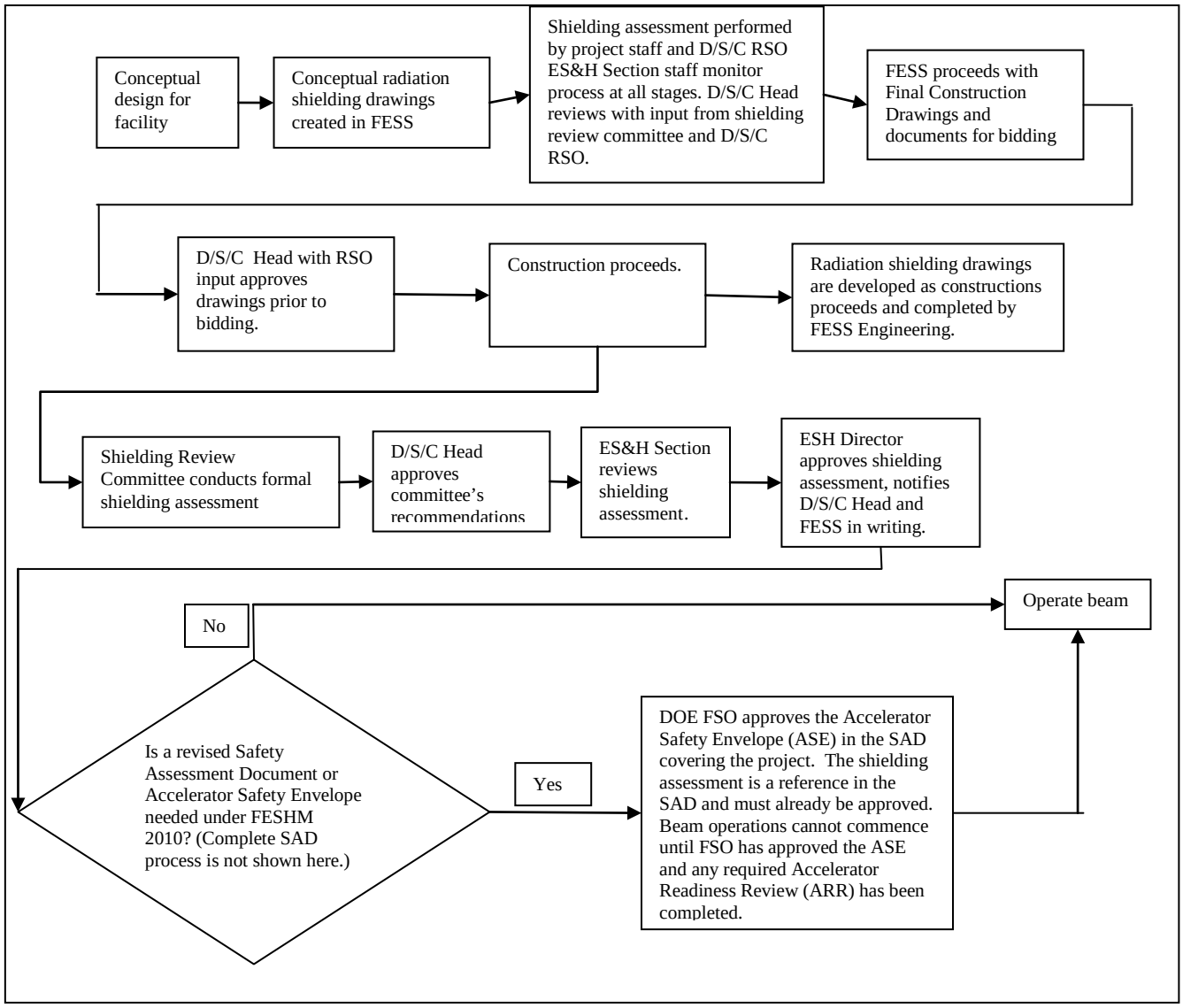

Fig. 8-2 Fermilab Radiation Shielding Design Review Process

1. Division/Section/Center Heads are responsible for accelerator/beamline operations and those of the associated experimental program that operated within their assigned physical spaces. These responsibilities include the fulfillment of these program elements:

    a. Develop and maintain a comprehensive inventory of beamline shielding against ionizing radiation in the areas assigned to them by the Director, and assure that the shielding complies with provisions of this manual. The inventory most likely will take the form of a set of civil construction drawings overlayed with beamline components maintained in an accessible electronic format. Portable or movable shielding and devices installed either temporarily or permanently within larger, permanent facilities that are required to achieve a given level of radiation protection shall be documented, perhaps on overlays to civil construction drawings.

    b. Conduct a shielding assessment when new experiments are installed or when new beamlines are commissioned. Such assessments shall also be conducted when beamline operating conditions change such that the official "as-built" drawings maintained by the Facilities Engineering Services Section must be changed, or if the operating conditions (available intensity, energy, or particle type, etc.) result in a change to the access conditions (see Article 236) applicable to a given area.

        (1) The shielding assessment shall be a written description that includes calculations and measurements of possible radiation exposures, radiation shielding, beam optics and other relevant information. It shall address soil and groundwater contamination, airborne radionuclide releases and any associated required monitoring activities.

        (2) A preliminary shielding assessment should be conducted at the design specification stage of conceptual development including, project staff, the Division/Section/Center Radiation Safety Officer (RSO), and those responsible for designing the facility. Where civil construction is needed, representatives of the Facilities Engineering Services Section shall be included. This specification stage should identify the desired personnel occupancy state for the final design.

        (3) The shielding assessment must document the circumstances and controls that serve to limit the intensity of the maximum beam loss and/or its duration. This specifically includes a description of required portable or movable shielding and beamline components.

(4) The final assessment shall establish the occupancy status and radiological posting requirements of areas with respect to the posting criteria of Articles 234 and 236.

(5) The final assessment shall be reviewed internally within the originating division/section/center (and within any other affected division/section/center) and approved in writing by the responsible division/section/center head(s).

(6) Modifications to shielding configurations, including required moveable or portable shielding shall be reviewed by the Facilities Engineering Services Section (FESS) for structural engineering impact. Changes to the original set of "as-built" drawings to incorporate the placement of such movable or portable shielding once it is installed shall be coordinated with FESS.

(7) The final shielding assessment shall be submitted to the Senior Radiation Safety Officer (SRSO) for review in a timely manner prior to the conduct of the operations covered in the assessment.

(8) The shielding assessment shall be reviewed by the Shielding Assessment Review Subcommittee of the Fermilab ES&H Committee (FESHCom) in accordance with its charter found at https://esh-docdb.fnal.gov:440/cgi-bin/ShowDocument?docid=1089).

(9) The shielding assessment documentation, including analysis, beamline layout schematics, and civil construction drawings, shall be maintained as current documents, inclusive of drawings stored in a central electronic depository accessible to all affected organizations. These documents shall be maintained in accordance with provision (6) above.

(10) Shielding assessments and their approvals are generally based upon design and construction drawings, inclusive of field modifications and other related documents as they arise during the construction process.

(11) The shielding assessment, at least at a preliminary level, shall be approved prior to project being released for bid. Such a preliminary approval shall be clearly labeled as such and the criteria for final approval clearly documented.

(12) Upon project/modification completion, a final set of "as-built" drawings shall be produced to document conditions as of project

completion. These drawings shall be maintained in accordance with provision (8) above.

(13) FESS Engineering shall be provided copies of all final approval documents for inclusion in its site-specific shielding file.

(14) The Accelerator Division has developed and maintains an established protocol for conducting such shielding assessments. This document is denoted ADSP-02-0110.

c. Maintain documentation of the shielding of beamlines in their area of responsibility and determine and document appropriate beam operating parameter limits required to meet ES&H requirements specified both in the FRCM and in FESHM 2010. This includes the Accelerator Safety Envelope (ASE) elements that are connected with radiological shielding.

d. Coordinate these responsibilities in regions of interface between all affected divisions/sections/centers.

e. Control the placement of temporary shielding in accelerator/beamline enclosures by some or all of the following provisions:

(1) appropriate labeling and securing of such shielding to prevent its inadvertent removal,

(2) appropriate procedures for evaluating its effectiveness, and integrity,

(3) appropriate documentation, which becomes part of the permanent record of the operation.

f. Implement procedures to assure proper review and control of temporary modifications to permanent shielding that do not meet the criteria of 1.b.

2. As-built shielding documents shall be prepared and maintained.

a. FESS shall prepare and maintain the original set of “as-built” drawings documenting the status of radiation shielding for civil structures.

b. FESS shall be provided copies of all approved documentation as a given project proceeds through the design process.

c. Divisions/sections/centers shall augment such drawings to encompass required portable shielding or devices and provide this documentation to FESS.

d. The drawings shall be approved by the responsible division/section/centers at 3 stages; conceptual design (meaning development of specifications), prior to bidding, and as-built.

e. Thereafter FESS will maintain the up-to-date originals of the civil drawings (and retain archival drawings of past conditions) while the ES&H Section and the appropriate division/section/center will be supplied up-to-date copies of the current shielding conditions.

3. The Senior Radiation Safety Officer (SRSO) shall:

a. Review the shielding assessment and approve of it if requirements of this Manual are met.

b. Maintain records of such reviews including file copies of the "as-built" shielding documents including drawings and the shielding assessment documentation and review protocols.

4. Approvals of these documents may be done in an electronic format. The electronic approvals shall clearly indicate the version being approved by document number, date, etc.

APPENDIX
Brief Synopsis of Methodologies for Assessing the Shielding of Particle Accelerators

At high energy particle accelerators the design of adequate shielding becomes complex with increasing beam energy due to cascade phenomena. A high-energy hadron interacting with a nucleus typically creates a rather large number of short-lived particles (pions, kaons, etc.), as well as protons, neutrons and nuclear fragments. Another important result of high-energy hadron interactions is the production of muons, which can represent a significant shielding problem. The interactions of the high energy beams can also produce significant radioactivation of the beamline components, the prompt radiation shield, and the surrounding environment. Even hadrons of relatively low energies can produce significant radiation fields and the possibility of radioactivation of materials including environmental media.

Likewise, electrons of all energies can produce significant prompt radiation fields. At the lowest energies these radiation fields are dominated by photons. Above kinetic energies of a few MeV neutrons can be produced by electron interactions with matter while above 211 MeV muon radiation fields are possible. In the environs of electron radiation fields, residual radioactivity can be produced. Thus the shielding of radiation fields associated with electron beams and even muon beams can also be important at Fermilab, especially as the program of the Laboratory continues to be developed and future facilities designed, constructed, and operated.

Shielding design at Fermilab shall be performed in a high quality manner. A great deal of expertise on this topic is available in the ES&H Section, the Accelerator Physics Center, and the Accelerator Division as well as individuals located elsewhere within the Laboratory. A large body of documentation is available on these issues in publications, Fermilab reports (TMs, FNs, Confs, and Pubs.) and in published literature in accelerator science and health physics.

Many practical problems are amenable to phenomenological approaches of longstanding use at Fermilab and elsewhere. Some of these approaches are clearly of benefit in job planning activities, etc. However, for new designs in most circumstances it is far better to perform calculations specific to the details of the shielding configuration encountered than it is to excessively employ generalized calculations and “rules of thumb”. Thus, when practicable, modern shielding codes such as MARS should be used in accordance with FESHM Chapter 5201, "Usage of Computer Calculations Affecting Environment, Safety, and Health." Proper use of shielding computer models at the design stage can prevent design errors that are typically costly and difficult to correct.

A detailed technical description of radiation physics at accelerators along with many more applicable references is found in Reference Fermilab TM-1834, “Radiation Physics for Personnel and Environmental Protection” by J. D. Cossairt, posted on the following website:
https://esh-docdb.fnal.gov:440/cgi-bin/ShowDocument?docid=1007.

This document contains an extensive, but not exclusive, bibliography of references that are available for further use.