

**ANS**

Calculation and Measurement of Direct and Scattered Gamma Radiation from LWR Nuclear Power Plants

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An American National Standard

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**American National Standard
Calculation and Measurement of Direct and Scattered
Gamma Radiation from LWR Nuclear Power Plants**

Secretariat
American Nuclear Society

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American National Standard

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Foreword

(This foreword is not a part of American National Standard, “Calculation and Measurement of Direct and Scattered Gamma Radiation from LWR Nuclear Power Plants,” ANSI/ANS-6.6.1-2015.)

In mid-1973, a need for a standard on this subject was identified by D. K. Trubey, chairman of ANS-6. The proposed standard had been listed among those having a high priority by the Atomic Energy Commission Directorate of Regulatory Standards. The project was assigned by the NTAB Executive Committee in September 1973. Working Group ANS-6.6 was formed and E. A. Warman was appointed chairman in September 1973. The first meeting of the working group was held in November 1973. Twelve subsequent meetings were held from February 1974 through June 1978.

When preparing the initial version of this standard, the 1973 working group provided a series of reference calculations with which a radiation analyst should compare results obtained by the method he/she elected to use in a given application. Comparison with the results of these reference calculations is intended to provide some assurance that the methods being considered by this standard’s user produce results that are in reasonable agreement with those of other methods. These reference calculations are intentionally simplistic to make this comparison effort easier to accomplish.

The first working draft was completed in June 1975. A revised working draft was distributed for initial review by ANS-6 chairs in June 1976. The completed first draft (Draft 1) was submitted to ANS-6 for ballot in September 1977. This draft was unanimously approved in subsequent balloting by ANS-6 subcommittee chairs, with the sole negative ballot being changed to affirmative after resolution of comments. A reorganized working group, ANS-6.6.1, was established in 2012 to reconsider the status of the standard. In June 2013, that working group recommended revisions of the standard to (a) correct editorial errors, (b) update the list of referenced documents, (c) update the definitions and units of the dose terms, (d) update Figs. 6.3 through 6.8 to include dose rate results for the reference calculations computed based on a modern Monte Carlo (MCNP5) computer program, and (e) incorporate three new tables (Tables 6.3, 6.4, and 6.5) providing the MCNP5-computed dose rate results and their relative statistical uncertainty.

This standard addresses contained sources of direct and scattered radiation and specifically excludes effluent releases and accident sources. Measurements at some operating plants, which have no local shielding to reduce reactor cavity nozzle inspection port streaming, have indicated that localized streaming can be measurable outside the containment. Such localized streaming effects are not addressed in this standard.

Particular emphasis is placed on the direct and scattered radiation from ^{16}N sources in boiling water reactors (BWRs). This emphasis reflects the fact that analysis and ^{16}N measurement of radiation associated with sources at BWRs was identified as a major area of interest in establishing priority for development of this standard. The three appendices to the standard are included as examples of the type of measurements and analyses that have been performed in connection with the ^{16}N sources at BWRs. In Appendices A and B, the assumption is made that the observed dose rates are entirely the result of ^{16}N activity. The net effect of this assumption is to increase the amount of conservatism in the quantification of the source terms, in that other radiations are included in the measurements from which the ^{16}N source terms are developed.

This standard might reference documents and other standards that have been superseded or withdrawn at the time the standard is applied. A statement has been included in Sec. 8, References,” that provides guidance on the use of references.

This standard does not incorporate the concepts of generating risk-informed insights, performance-based requirements, or a graded approach to quality assurance. The user is advised that one or more of these techniques could enhance the application of this standard.

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Contents

Section	Page
1 Scope.....	1
2 Applicable documents	1
3 Terms and definitions	1
3.1 Acronyms	1
3.2 Shall, should, and may	2
3.3 Definitions	2
4 Requirements	3
5 Dose assessment guidelines	4
6 Calculations	4
6.1 General introduction	4
6.2 Sources	5
6.2.1 Sources inside shielded buildings	5
6.2.2 Sources outside shielded buildings	5
6.3 Source modeling (mathematical representations)	5
6.3.1 Source strengths and assumptions.....	6
6.3.2 Geometric considerations.....	7
6.4 Geometric modeling (shielding and plant layout).....	8
6.5 Site topography.....	8
6.6 Radiation transport methods	9
6.6.1 Acceptable methods.....	9
6.6.2 Reference calculations	10
6.6.2.1 Reference calculations I.1	10
6.6.2.2 Reference calculations I.2	10
6.6.2.3 Reference calculations II.1	10
6.6.2.4 Reference calculations II.2.....	10
7 Measurement constraints and interpretation of data	14
7.1 General considerations.....	14
7.2 Measurement techniques	21
7.2.1 Thermoluminescence dosimeters.....	21
7.2.2 Ionization chambers.....	22
7.2.3 Gamma-ray spectrometry.....	23
7.3 Measurement techniques summary	24
8 References.....	24
Tables	
Table 6.1	6
Table 6.2	7
Table 6.3	13
Table 6.4	13
Table 6.5	14
Table A.1	28
Table A.2	29
Table B.1	35

Table B.2	35
Table B.3	36
Table B.4	36
Table B.5	36
Table B.6	36

Figures

Fig. 6.1	Geometric configurations for Reference Problem I.1 and I.2	11
Fig. 6.2	Geometric configurations for Reference Problem II.1 and II.2	11
Fig. 6.3	Scattered dose rate as a function of horizontal distance for Reference Problem I.1	15
Fig. 6.4	Total dose rate as a function of horizontal distance for Reference Problem I.1	16
Fig. 6.5	Scattered dose rate as a function of horizontal distance for Reference Problem I.2	17
Fig. 6.6	Total dose rate as a function of horizontal distance for Reference Problem I.2	18
Fig. 6.7	Total dose rate as a function of horizontal distance for Reference Problem II.1	19
Fig. 6.8	Total dose rate as a function of horizontal distance for Reference Problem II.2	20
Fig. A.1	Dose point designations and locations	29
Fig. B.1	Cooper nuclear power station	33
Fig. B.2	Duane Arnold Energy Center	34
Fig. B.3	Steam line radiation monitor readings	35
Fig. C.1	Distance from source (meters)	38

Appendices

Appendix A	Semi-Empirical Determination of ^{16}N -Specific Activity at an Operating Boiling Water Reactor.....	27
Appendix B	Estimates of ^{16}N -Specific Activity from Main Stream Line Measurements at a 1600-MWt and a 2400-MWt Boiling Water Reactor.....	30
Appendix C	Measurements of ^{16}N Gamma Radiation Fields Near Operating Boiling Water Reactors	37

Calculation and Measurement of Direct and Scattered Gamma Radiation from LWR Nuclear Power Plants

1 Scope

This standard defines calculational requirements and discusses measurement techniques for estimates of dose rates near light water reactor (LWR) nuclear power plants because of direct and scattered gamma rays from contained sources on-site. On-site locations outside plant buildings and locations in the off-site unrestricted area are considered. All sources that contribute significantly to dose rates are identified and methods for calculating the source strength of each are discussed. Particular emphasis is placed on ^{16}N sources as they are significant sources of direct and scattered radiation for boiling water reactors (BWRs). The standard specifically excludes radiation from gaseous and liquid effluents. The standard describes the considerations necessary to compute dose rates, including component self-shielding, shielding afforded by walls and structures, and scattered radiation. The requirements for measurements and data interpretation of measurements are given. The standard includes normal operation and shutdown conditions but does not address accident or normal operational transient conditions. The standard also applies to the gamma dose resulting from dry fuel storage facilities.

2 Applicable documents

The following documents supplement or support this standard:

Glossary of Terms in Nuclear Science and Technology [1].¹⁾

ANSI/ANS-6.4-2006, "Nuclear Analysis and Design of Concrete Radiation Shielding for Nuclear Power Plants" [2].

ANSI/ANS-18.1-1999 (withdrawn), "Radioactive Source Term for Normal Operation of Light Water Reactors" [3].

3 Terms and definitions

3.1 Acronyms

BWR: boiling water reactor

LWR: light water reactor

PWR: pressurized water reactor

RPV: reactor pressure vessel

TLD: thermoluminescence dosimeter

¹⁾Numbers in brackets refer to corresponding numbers in Sec. 8, "References."

3.2 Shall, should, and may

The word “shall” is used to denote a requirement; the word “should” is used to denote a recommendation; and the word “may” is used to denote permission, neither a requirement nor a recommendation.

3.3 Definitions

The following special definitions will be useful in understanding this and companion or references standards.

A number of terms are used in this standard as defined in textbooks on the subject of radiation shielding and radiation detection. They are not used in any special sense in this standard.

capacity factor: The capacity factor is defined as the energy actually supplied by a plant in a given time interval, divided by the product of the design power and the time interval. The capacity factor may be used in assessing the annual absorbed dose, provided the principal sources are directly related to capacity.

direct gamma rays: The term direct gamma rays is used to denote those gamma rays that do not undergo scattering interactions in transit from the source volume to the receptor location. It differs from “uncollided gamma rays” in that scattering internal to distributed sources (such as a pipe containing radioactive fluid) may be included in the direct category.

dose rate and absorbed dose: The term dose is used herein to refer to either exposure (roentgens), absorbed dose (rad or gray), dose equivalent (rem or sievert), or ambient dose equivalent (rem or sievert). These latter terms are specifically defined in Report 51 of the International Commission on Radiation Units and Measurements [4]. For gamma rays, to the degree of approximation acceptable, for practical purposes, and for the purposes of this standard, the absorbed dose, dose equivalent, and ambient dose equivalent may be considered numerically equivalent.

essentially unshielded: As used in this standard, essentially unshielded relative to air scattering means less than one mean-free-path of attenuation for the dominant energy. If the users of this standard choose to use an alternative definition in their calculations, the users should clearly define its use in documenting their calculations.

power level: The power level is the power production in units of thermal megawatts. In the context of this standard, the user is cautioned pertaining to scaling by power level in that specific sources of gamma radiation may not exhibit a linear relationship with power level, because of the influence of other parameters, such as coolant flow rate.

scattered gamma rays: The term scattered gamma rays is used to describe all gamma rays that have undergone scattering interactions in transit between the source volume and receptor locations. This category includes air scattering, ground scattering, and scattering through or off any intervening structures or shields.

special uses of direct and scattered categories: Because of the limitations of some computer programs (e.g., some point kernel approaches), it may not be possible to compute direct and scattered gamma-ray components as defined in the previous definition. If the user of this standard requires a special use of the terms direct and scattered, this special use shall be clearly identified, and definitions appropriate to the specific calculational procedure should be provided by the analyst.

4 Requirements

To facilitate the use of this standard, the various requirements called out in subsequent sections have been combined into this section. Following is a concise listing of the requirements of this standard:

Requirement	Reference Section
If the user of this standard requires a special use of the terms “direct” and “scattered,” this special use shall be clearly identified, and definitions appropriate to the special calculational procedure should be provided by the analyst.	3
All significant sources of gamma radiation that are essentially unshielded (e.g., 4 ft. or less of concrete) relative to air scattering (i.e., shielded on the sides but essentially unshielded on the top) shall be considered.	6.2.1
All sources of gamma radiation that are located outside of shielded buildings shall be considered.	6.2.2
To accurately describe source strengths in quantitative terms, the starting bases and subsequent effects of processing steps on radiation streams shall be evaluated.	6.3.1
The geometrical models used to describe the sources for radiation transport calculations shall be discussed.	6.3.2
Piping arrangements shall be reviewed and a model constructed that includes piping sources that could contribute significantly to direct and scattered radiation dose rates.	6.4
Shielding in any form credited in the analysis (e.g., walls, floors, ceilings, etc.) shall be represented in the model.	6.4
The location of sources and relative orientation of shield walls and floors shall be clearly delineated.	6.4
The moisture separator/reheaters and associated piping shall be considered for air scattering if they are located on the turbine operating floor with some unshielded paths for gamma rays to escape the building.	6.4
The direct radiation contribution from all sources, irrespective of location, shall be evaluated in accordance with the requirements of Sec. 6.2 of this standard.	6.4
To provide an understanding of what is reported as direct and scattered radiation, the user of this standard shall clearly state which components of the radiation transport analysis are included in each category in a specific analysis.	6.6.1
Comparisons shall be made between the results of reference problem solutions provided by the methods employed in a specific power plant analysis and the results of the reference calculations presented in Sec. 6.6.2.	6.6.1
The method of calculating the radiation transport shall be adequately documented to allow for independent verification of results by specialists in the radiation transport field.	6.6.1
All input parameters and assumptions associated with geometric considerations and source strengths shall be clearly documented.	6.6.1
If a scaling approach is used, adequate justification shall be provided, including a discussion of the similarities and differences between the power plant in question and the one used as the basis for the scaling.	6.6.1

5 Dose assessment guidelines

Two general areas of interest in performing dose rate calculations and measurements are the restricted area outside of the plant buildings and the unrestricted area or general environment as defined in *Code of Federal Regulations*, Title 10, “Energy,” and Title 40, “Protection of Environment” [5]. Guidance for specific locations has been developed [6, 7].

Dose rate calculations and measurements should be performed for areas outside of the plant buildings where personnel occupancy is expected. These areas include construction offices and construction areas for adjacent units, normal work areas of adjacent units and visitors’ centers. The selection of receptor points for dose rate calculations should be based on consideration of the occupancy factors and number of personnel, the construction schedule, and shielding at the receptor location where appropriate. The calculations should be for a sufficient number of locations to serve as input for dose estimates in units of person-rem (or person-Sv) for construction workers and for use of other on-site areas. These units represent the summation of all individual doses (rem or Sv) acquired by the personnel during their occupancy times.

Dry fuel storage facilities has gamma and neutron contributions to the total dose, which should be considered. Also, the dose contribution from activation gammas because of absorption of the neutrons should be evaluated.

Special locations that can be exposed to direct or scattered radiation, such as personnel dosimeter racks stored in guard stations, may also have to be considered.

In certain cases, it might be necessary to calculate dose rates at on-site locations to which the public has access, such as visitors’ centers, navigable waters, and recreational areas. In such cases, conservative estimates of annual occupancy times should be included in the dose assessments and be clearly identified (i.e., hours occupancy/year) at each location.

Dose rate calculations or measurements, or both, should be performed for locations at the boundary of the restricted area and for specific locations in the restricted area (e.g., nearby residences, schools, hospitals, and other publicly used facilities). Because of the extremely rapid decrease of direct and scattered radiation with distance from the source, the dose rates at some of these locations may be insignificant [$<10^{-3}$ rem/yr (10^{-2} mSv/yr)].

The continuous dose rate and the expected annual dose, based on occupancy times, should be documented for each location. The assumed occupancy factors should be clearly indicated at each location. For normal operational sources, the plant capacity factor should be incorporated.

In cases in which the source intensity is affected by the power level, the plant capacity factor should be considered.

Temporal variations in the sources should be accounted for in the annual dose (e.g., times that a tank is completely or partially filled with radioactive fluid).

Care should be taken to use minimum reasonable tank fluid levels for shielding to avoid a situation in which unmonitored sites could increase dose because of a tank’s level change whose fluid was incorporated as a shield.

6 Calculations

6.1 General introduction

This section discusses documentation, sources, source modeling, geometric modeling (shielding and plant layout), site topography, and radiation transport methods.

An important part of calculations of the type discussed in this standard is adequate documentation. This documentation should be complete enough to cover assumptions, methods of analysis, and so on, which affect the results of the calculations. The form of the documentation the user of this standard chooses to employ, however, is at the user's discretion. It may, or may not, be a formal or informal report. It may simply be completed engineering calculations written up in a manner in accordance with a given firm's quality assurance requirements and filed in appropriate project job books. Irrespective of the form, the requirements and recommendations pertaining to documentation that are contained in this standard should be given careful consideration by the user.

Locations to be considered in calculating direct and scattered radiation levels outside of buildings are identified. Reference calculations are provided to permit comparison with methods of calculations chosen for use in specific applications by individual investigators or analysts.

6.2 Sources

Tables 6.1 and 6.2 list significant sources of radiation in BWRs and pressurized water reactors (PWRs), respectively, which should be considered within the constraints delineated in Secs. 6.2.1 and 6.2.2. Additional sources may need to be considered depending on the specific plant design.

In determining the significant sources, the fraction of the time over a calendar year during which individual sources would contribute to dose rates outside buildings should be evaluated (e.g., particular tanks may be considered to be full only several months in a given year).

Appropriate reference should be made to available supporting documentation, such as tables, figures, and flow diagrams.

6.2.1 Sources inside shielded buildings

All significant sources of gamma radiation (i.e., those listed in Tables 6.1 and 6.2) that are essentially unshielded relative to air scattering (i.e., shielded on the sides but essentially unshielded on the top) shall be considered. Sources that are shielded only by the outside shield wall of a building should be considered. Direct radiation contributions need not be considered for sources that are shielded by the equivalent of >4 ft. (1.22 m) of ordinary concrete.

Sources in the reactor containment building need not be considered provided at least 4 ft. of ordinary concrete or equivalent shielding is provided for direct radiation, and 2 ft. (0.61 m) of ordinary concrete, or equivalent, for air scattering.

6.2.2 Sources outside shielded buildings

All sources of gamma radiation that are located outside of shielded buildings shall be considered.

6.3 Source modeling (mathematical representations)

Source modeling, as discussed herein, includes geometric considerations and source strength determinations. Shielding around sources is discussed in Sec. 6.4. Any self-shielding, associated with the sources themselves, is included as part of the source modeling.

6.3.1 Source strengths and assumptions

To accurately describe source strengths in quantitative terms, the starting bases and the subsequent effects of processing steps on radioactive streams shall be evaluated. The starting bases consist of the reactor coolant concentrations (fission products and activation products); the ^{16}N -specific activity leaving the reactor pressure vessel nozzle; and, for ^{16}N sources in BWRs, the heat balance for the steam cycle. For ^{16}N sources, the transit time through piping and equipment and the relative quantities of liquid and steam inside components during their normal equilibrium operation are the major processing data required. The ^{16}N -specific activity in BWR coolant is sensitive to water chemistry, and the process of direct hydrogen addition may lead to a several-fold increase in activity over that otherwise experienced.²⁾

In the absence of specific source strengths that may be employed for a specific plant, the source strengths reported in ANSI/ANS-18.1-1999 [3] should be employed, to the extent that they are deemed to be applicable by the user of the standard.

There are U.S. Nuclear Regulatory Commission–specific requirements for LWRs in NUREG-0800 and Regulatory Guides that also govern the source terms that need to be applied in licensing bases, namely Sec. 12.2, “Radiation Sources,” and Chapter 15, “Transient and Accident Analyses,” of NUREG-0800, RG 1.183, and RG 1.89 [8, 9, 10, 11].

Processing steps and factors that should be evaluated include such quantities as demineralizer and filter decontamination factors, partition factors (fraction of isotope carried into steam from reactor water), and transit time through piping and equipment. For radwaste sources, the carryover factor, filters, and demineralizer decontamination factors and flow rates are the most pertinent data.

**Table 6.1 – Contained sources in shielded buildings to be considered
in boiling water reactor plants¹⁾**

Main Steam Piping in Turbine Building
High-Pressure Turbines
Low-Pressure Turbines
Moisture Separator/Reheaters
Feed-Water Heaters
Off-Gas System
Extraction Steam Piping
Phase Separator Tanks
Filters
Demineralizers
Evaporators
Evaporator Bottom Tanks
Radwaste Storage, including Dry Fuel Storage Facilities

¹⁾See Secs. 6.2.1 and 6.2.2.

²⁾Some results of the determination of ^{16}N -specific activity by means of measurement of the external dose rates from steam lines at operating BWRs are reported in Appendices A and B. These results are for plants not employing direct hydrogen addition to the coolant.