CONTROL ROOM DESIGN CRITERIA AND RADIOLOGICAL HEALTH EFFECTS

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With the increased interest in modernized power reactor fuels, including accident tolerant fuels and higher burnup and increased enrichment fuels, by U.S. Nuclear Regulatory Commission (NRC) licensees and industry, the NRC is considering a rulemaking to enable the application of these modern fuel designs in an efficient manner. To support this rulemaking determination, the Increased Enrichment Working Group, through the Office of Nuclear Reactor Regulation (NRR), sought assistance from the Office of Nuclear Regulatory Research (RES) with informal assistance request (IAR) NRR-2022-019, "Assessment of Radiation Protection Recommendations for Emergency Workers," (August 26, 2022). The purposes of IAR NRR-2022-019 were to identify NRC regulations that apply radiological consequences- as operational limits or design criteria, to describe the regulatory approaches that are applicable to workers during normal and emergency conditions, to develop an annotated bibliography of selected radiation protection recommendations that are applicable during an emergency, and to provide an assessment of the identified design criteria to the contemporary understanding of radiological health effects.

NRC radiological regulations are based to a significant extent on the recommendations of the International Commission on Radiological Protection (ICRP) and on the U.S. National Council on Radiation Protection and Measurements (NCRP). Meanwhile, the Federal Emergency Management Agency (FEMA) is the Federal agency of the U.S. Department of Homeland Security responsible for helping people before, during, and after disasters. For radiological incidents, the U.S. Environmental Protection Agency (EPA) is the primary Federal agency that establishes protective action guides and planning guidance for radiological incidents. These organizations establish dose-based criteria that are deemed sufficiently low to preclude deterministic health effects. Therefore, these protective dose-based criteria provide an adequate margin that would maintain the operator's ability to maintain a reactor in a safe condition under accident conditions.

The RES staff found that there is ample operating and licensing experience, scientific data, and technical information; numerous recommendations from national and international organizations responsible for radiation protection standards; probabilistic risk assessment technology; and regulatory precedence that support a reevaluation of the control room design criteria of General Design Criteria (GDC) 19, "Control room," in Appendix A, "General Design Criteria for Nuclear Power Plants," to Title 10 of the *Code of Federal Regulations* (10 CFR) Part 50, "Domestic Licensing of Production and Utilization Facilities," and 10 CFR 50.67(b)(2)(iii). This review of the radiological framework for the control room design criteria provides, in part, an initial basis for NRC's realignment with the current ICRP and NCRP recommendations and the FEMA and EPA federal response guidelines.

ABBREVIATIONS

10 CFR	Title 10 of the *U.S. Code of Federal Regulations*
ADAMS	Agencywide Documents Access and Management System
ALARA	as low as is reasonably achievable
ATF	accident tolerant fuel
DBA	design-basis accident
EPA	U.S. Environmental Protection Agency
FEMA	Federal Emergency Management Agency
FR	*Federal Register*
GDC	general design criterion/criteria
GWd	gigawatt-day(s)
Gy	gray(s)
IAR	informal assistance request
ICRP	International Commission on Radiological Protection
LD 50/60	lethal dose to 50 percent of the people within 60 days without medical treatment
LPZ	low population zone
LWR	light-water reactor
MTU	metric ton(s) of uranium
NCRP	National Council on Radiation Protection and Measurements
NEIMA	Nuclear Energy Innovation and Modernization Act
NRC	U.S. Nuclear Regulatory Commission
NRR	Office of Nuclear Reactor Regulation
rem	roentgen equivalent man
RES	Office of Nuclear Regulatory Research
SRM	staff requirements memorandum
SSC	structure, system, and component
Sv	sievert(s)
TEDE	total effective dose equivalent
U	uranium

1. INTRODUCTION

With the increased interest in modernized power reactor fuels, including accident tolerant fuels (ATFs) and higher burnup and increased enrichment fuels, by U.S. Nuclear Regulatory Commission (NRC)-licensees and industry, the NRC is considering a rulemaking to enable the application of these modern fuel designs in an efficient manner. To support this rulemaking determination, the Increased Enrichment Working Group, through the Office of Nuclear Reactor Regulation (NRR), sought assistance from the Office of Nuclear Regulatory Research (RES) with informal assistance request (IAR) NRR-2022-019, "Assessment of Radiation Protection Recommendations for Emergency Workers" [Ref. 1] (August 26, 2022). The purposes of IAR NRR-2022-019 were to identify NRC regulations that apply radiological consequences as operational limits or design criteria, to describe the regulatory approaches that are applicable to workers during normal and emergency conditions, to develop an annotated bibliography of selected radiation protection recommendations that are applicable during an emergency, and to provide an assessment of the identified design criteria to contemporary understanding of radiological health effects. This IAR is expected to help inform the NRC's increased enrichment rulemaking activities and ultimately enhance the agency's ability to perform its mission when considering and licensing fuels that apply increased enrichments. This report provides the results of the IAR.

2. BACKGROUND

ATFs are a set of new nuclear fuel technologies that have the potential to enhance safety at U.S. nuclear power plants by offering better performance during normal operation, transient conditions, and accident scenarios. On January 14, 2019, the President signed into law the Nuclear Energy Innovation and Modernization Act (NEIMA). NEIMA Section 107, "Commission Report on Accident Tolerant Fuel," defines ATF as a new technology that does the following:

> (1) makes an existing commercial nuclear reactor more resistant to a nuclear incident (as defined in section 11 of the Atomic Energy Act of 1954 (42 U.S.C. 2014)); and
>
> (2) lowers the cost of electricity over the licensed lifetime of an existing commercial nuclear reactor.

Based on stakeholder interactions, the staff is aware that industry plans to request higher fuel burnup limits (i.e., above 62 gigawatt-days per metric ton of uranium (GWd/MTU) rod average) along with the deployment of ATF concepts. To achieve higher burnup limits, industry will need to request increases in fuel enrichment from the current standard of 5.0 weight percent uranium (U)-235 up to approximately 10.0 weight percent U-235. In February 2019, industry identified potential advantages of increased enrichment fuel for light-water reactors (LWRs) in the Nuclear Energy Institute white paper "The Economic Benefits and Challenges with Utilizing Increased Enrichment and Fuel Burnup for Light-Water Reactors," issued February 2019 [Ref. 2]. In September 2021, the NRC staff issued an update to the "Project Plan to Prepare the U.S. Nuclear Regulatory Commission for Efficient Licensing of Accident Tolerant Fuels," Version 1.2 [Ref. 3], that described the pursuit of higher burnup and increased enrichment as key components of industry ATF efforts. Industry plans to deploy batch loads of fuels enriched to levels greater than the current standard of 5.0 weight percent U-235 by the mid to late 2020s.

The development of the current regulatory framework did not foresee enrichments greater than 5.0 weight percent U-235, and thus regulations were generally established with the expectation that enrichments would be below this value with reasonable bounding assumptions contained within the safety analysis methodologies. However, some specific regulations discuss such enrichments, such as Title 10 of the *Code of Federal Regulations* (10 CFR) 50.68(b)(7) [Ref. 4], which requires that U-235 enrichment levels in power reactor fuel be no more than 5.0 percent by weight.

In response to industry interest in LWR fuels enriched to between 5.0 to 10.0 weight percent U-235, the NRC staff submitted a rulemaking plan in SECY-21-0109, "Rulemaking Plan on Use of Increased Enrichment of Conventional and Accident Tolerance Fuel Designs for Light-Water Reactors," dated December 20, 2021 [Ref. 5], requesting Commission approval to initiate rulemaking to amend NRC requirements to facilitate the use of LWR fuel containing uranium enriched to greater than 5.0 weight percent U-235. If left unchanged, the regulatory framework can accommodate the use of LWR fuel containing enrichments greater than 5.0 weight percent U-235 using licensee-specific exemptions. However, because of the widespread interest in these new fuels, the staff expects many licensees to pursue their use, meaning that the staff may have to process many exemptions to meet industry demand. In SECY-21-0109, the staff recommended rulemaking to reduce exemption requests and facilitate increased regulatory efficiency and consistency while continuing to ensure safety. Rulemaking on this topic would allow the staff to thoroughly review the potential regulatory implications of fuels enriched to greater than 5.0 weight percent U-235 and identify and assess the potential costs and benefits of changing regulatory requirements that impact their use. Rulemaking would also provide options for generic resolutions of these issues and invite stakeholder participation in decisions affecting this regulatory area, rather than on a case-by-case basis, as would result from the current regulatory framework.

The Commission approved the staff's proposal to initiate rulemaking to amend requirements for the use of LWR fuel containing uranium enriched to greater than 5.0 weight percent U-235 in Staff Requirements Memorandum (SRM)-SECY-21-0109, dated March 16, 2022 [Ref. 6]. The Commission stated that the provisions of the rule should only apply to high-assay low-enriched uranium[1] fuel, both for nonproliferation and safeguard reasons and to focus the staff's analysis on the range of enrichment most likely to be contemplated in future commercial applications.

In addition, the Commission directed the staff to take the following actions in this rulemaking:

- In the regulatory basis and guidance, the staff should appropriately address and analyze fuel fragmentation, relocation, and dispersal issues relevant to fuels of high enrichment and burnup levels.

- The staff should work expeditiously with stakeholders to identify and develop necessary regulatory guidance and technical bases to support the effective and efficient licensing of increased enrichment applications.

[1] Uranium fuel enriched to greater than 5.0 and less than 20.0 weight percent U-235.

- The staff should take a risk-informed approach when developing this rule and the associated regulatory basis and guidance.

- The staff should reexamine the schedule to determine whether key milestones can be achieved sooner than projected by leveraging ongoing regulatory innovation efforts.

Several performance-based regulations use radiological acceptance criteria. Both 10 CFR 50.67(b)(2) [Ref. 7] and General Design Criterion (GDC) 19, "Control room" of Appendix A, "General Design Criteria for Nuclear Power Plants," to 10 CFR Part 50, "Domestic Licensing of Production and Utilization Facilities" [Ref. 8], provide a specific dose-based criterion of 5 rem (50 millisievert (mSv)) total effective dose equivalent (TEDE) for demonstrating the acceptability of the control room design. They represent a distinct layer of defense in depth that assumes a major accident that results in substantial meltdown of the reactor core with subsequent release of appreciable quantities of fission products. In application, they are "performance based," which require that a licensee or applicant provide a control room habitability design using traditional deterministic radiological consequence analyses methods to judge the acceptability of the design.

Overall, licensees' analysis of record DBA radiological consequence analyses has a relatively small margin to the control room design criteria to generally maximize operational flexibility. This has often resulted in instances in which licensees have had to perform additional analyses to demonstrate compliance without additional safety benefit. This has become unnecessarily burdensome and has often led to a focus on "safety versus compliance" debates between the NRC and licensees. In addition, the relatively small margin to the control room *design* criteria has resulted in the submission of license amendment requests for changes with low safety significance. It has also led to the occurrence of avoidable occupational exposures controlled by 10 CFR Part 20 in cases in which licensees have increased maintenance activities to meet the 5 rem (50 mSv) TEDE criterion.

With the prospect of licensing increased enrichments greater than 5.0 and less than 20.0 weight percent U-235, the staff anticipates that, to demonstrate compliance within their safety margin, licensees would need to continue performing potentially extensive analyses to demonstrate compliance within their safety margin with no or limited additional safety benefit. Further, industry representatives for LWRs have indicated they would be seeking enrichments up to 10.0 weight percent U-235 and that meeting the criteria when transitioning to increased enrichment fuel would be challenging. Therefore, industry organizations for LWRs have conveyed plans to commit resources to develop alternative approaches to demonstrate compliance with the design criteria.

The impact of increased power levels, enrichment, and subsequently fuel burnup on the results of the licensee's radiological consequence analysis of record for the computed DBA is multifaceted. However, a rule of thumb is that an increase in power level has a linear effect on computed radiological consequences. With an increase in U-235 enrichment necessary to reach the desired burnup level, the number of fissions within the reactor core source term also increases, which increases the resulting computed radiological consequences. The impact of

higher burnup on radiological consequences is nonlinear where the abundance of different radionuclides in the fuel peak at different burnup levels. This continuously changing radionuclide mix due to burnup has a varying impact on radiological consequences. Therefore, depending on how the reactor core is designed with increased U-235 enrichment fuel elements and operation at higher burnup levels to reach longer cycle time, the impact on radiological consequences computed to demonstrate compliance with the control room *design* criteria would increase and subsequently decrease the retained margin maintained by the licensee to provide operational flexibility.

The NRC recognizes the challenges that licensees face to retain margin within their licensing basis and the small amount of margin to the control room design criteria itself. The NRC does not want to unnecessarily penalize licensees for seeking increased enrichments that may then result in margin reductions and thereby requiring licensees to perform potentially extensive analyses to demonstrate compliance without a commensurate increase in safety.

This IAR requests RES staff to document its assessment findings in a publicly available memorandum to NRR. Additionally, the memorandum should provide for and identify the following tasks:

1. Identify applicable radiation dose-based regulations and their roles as operational limits or design criteria;

2. Describe the coherent regulatory approach to radiation protection for workers under normal and emergency conditions;

3. Perform an annotated bibliography of radiation protection recommendations for workers during emergency conditions from national and international organizations responsible for making recommendations for radiation protection standards; and

4. Provide an assessment of the identified design criteria to contemporary radiological health effects.

3. IAR TASK 1 RESULTS

Item 1: Identify applicable radiation dose-based regulations and their roles as operational limits or design criteria.

For this item, the RES staff researched the applicable regulations in various parts[2] of 10 CFR to summarize the dose-based siting and design criteria as well as occupational dose limits. Table 1 provides this summary.

[2] Specifically, the staff examined 10 CFR Part 50, 10 CFR Part 100, "Reactor Site Criteria," and 10 CFR Part 52, "Licenses, Certifications, and Approvals for Nuclear Power Plants."

Table 1 Dose-Based Criteria and Regulations

Regulation	Criteria	Operational Limit or Siting/Design Criteria
10 CFR 50.34(a)(ii)(D)(1) [Ref. 10]	0.25 sievert (Sv) 25 roentgen equivalent man (rem) total effective dose equivalent (TEDE) for any 2-hour period following postulated fission product release	Siting criteria
10 CFR 50.34(a)(ii)(D)(2)	0.25 Sv (25 rem) TEDE at low population zone (LPZ) boundary resulting from exposure to the radioactive cloud from postulated fission product release	Siting criteria
10 CFR 50.67(b)(2)(i)	0.25 Sv (25 rem)[a] TEDE for any 2-hour period following postulated fission product release	Design criteria
10 CFR 50.67(b)(2)(ii)	0.25 Sv (25 rem) TEDE at LPZ boundary resulting from exposure to the radioactive cloud from postulated fission product release	Design criteria
10 CFR 50.67(b)(2)(iii)	0.05 Sv (5 rem)	Design criteria
Appendix A to 10 CFR Part 50, GDC 19	0.05 Sv (5 rem)	Design criteria
10 CFR 52.17(a)(1)(ix)(A) [Ref. 11]	0.25 Sv (25 rem) TEDE for any 2-hour period following postulated fission product release	Design criteria
10 CFR 52.17(a)(1)(ix)(B)	0.25 Sv (25 rem) TEDE at LPZ boundary resulting from exposure to the radioactive cloud from postulated fission product release	Design criteria
10 CFR 52.47(a)(2)(iv)(A) [Ref. 12]	0.25 Sv (25 rem) TEDE for any 2-hour period following postulated fission product release	Design criteria
10 CFR 52.47(a)(2)(iv)(B)	0.25 Sv (25 rem) TEDE at LPZ boundary resulting from exposure to the radioactive cloud from postulated fission product release	Design criteria
10 CFR 52.79(a)(1)(vi)(A) [Ref. 13]	0.25 Sv (25 rem) TEDE for any 2-hour period following postulated fission product release	Design criteria
10 CFR 52.79(a)(1)(vi)(B)	0.25 Sv (25 rem) TEDE at LPZ boundary resulting from exposure to the radioactive cloud from postulated fission product release	Design criteria
10 CFR 52.137(a)(2)(iv)(A) [Ref. 14]	0.25 Sv (25 rem) TEDE at any point on the exclusion area boundary for any 2-hour period following the onset of the postulated fission product release	Design criteria
10 CFR 52.137(a)(2)(iv)(B)	0.25 Sv (25 rem) TEDE at LPZ boundary resulting from exposure to the radioactive cloud from postulated fission product release	Design criteria
10 CFR 52.157(c)(3)(d)(1) [Ref. 15]	0.25 Sv (25 rem) TEDE for any 2-hour period following postulated fission product release	Design criteria
10 CFR 52.157(c)(3)(d)(2)	0.25 Sv (25 rem) TEDE at LPZ boundary resulting from exposure to the radioactive cloud from postulated fission product release	Design criteria
10 CFR 100.11(a)(1) [Ref. 16]	whole body in excess of 0.25 Sv (25 rem)[b] or a total radiation dose in excess of 3 Sv (300 rem)[b] to the thyroid from iodine exposure for any 2-hour period following postulated fission product release	Siting criteria
10 CFR 100.11(a)(2)	Whole body in excess of 0.25 Sv (25 rem)[b] or a total radiation dose in excess of 3 Sv (300 rem)[b] to the thyroid from iodine exposure at LPZ boundary resulting from exposure to the radioactive cloud from postulated fission product release	Siting criteria

Regulation	Criteria	Operational Limit or Siting/Design Criteria
10 CFR 20.1206(e)(2) [Ref. 17]	Additional doses from planned special exposures and all doses in excess of limits shall not exceed the numerical limits in 10 CFR 20.1201(a) in 1 year (i.e., individuals can receive doses equal to a total of twice the limits in 10 CFR 20.1201(a)) not to exceed five times the doses in 10 CFR 20.1201(a) during an individual's lifetime (e.g., 0.25 Sv (25 rem))	Operational limit
10 CFR 20.1201(a)(i) [Ref. 18]	More limiting of (1) TEDE 0.05 Sv (5 rem) or (2) the sum of the deep-dose equivalent and committed dose equivalent to any organ or tissue of 0.5 Sv (50 rem). Other limits apply to lens of the eye and shallow-dose equivalent to the skin.	Operational limit

a. The use of 0.25 Sv (25 rem) TEDE is not intended to imply that this value constitutes an acceptable limit for emergency doses to the public under accident conditions. Rather, this 0.25 Sv (25 rem) TEDE value has been stated in this section as a reference value, which can be used in the evaluation of proposed design-basis changes with respect to potential reactor accidents of exceedingly low probability of occurrence and low risk of public exposure to radiation.

b. The whole body dose of 0.25 Sv (25 rem) referred to above corresponds numerically to the once in a lifetime accidental or emergency dose for radiation workers that, according to recommendations by the National Council on Radiation Protection and Measurements (NCRP), may be disregarded in the determination of their radiation exposure status (see National Bureau of Standards Handbook 69, "Maximum Permissible Body Burdens and Maximum Permissible Concentrations of Radionuclides in Air and in Water for Occupational Exposure," dated June 5, 1959 [Ref. 19]). However, neither its use nor that of the 3 Sv (300 rem) value for thyroid exposure as set forth in these site criteria guides are intended to imply that these numbers constitute acceptable limits for emergency doses to the public under accident conditions. Rather, this 0.25 Sv (25 rem) whole body value and the 3 Sv (300 rem) thyroid value have been set forth in these guides as reference values, which can be used in the evaluation of reactor sites with respect to potential reactor accidents of exceedingly low probability of occurrence, and low risk of public exposure to radiation.

Item 2: Describe the coherent regulatory approach to radiation protection for workers under normal and emergency conditions.

This section provides background on radiation protection regulations and practices during normal and emergency conditions. First, occupational dose limits are described because they pertain primarily to normal operating conditions—the conditions most prevalent during power plant operations. Then the control room design criteria are described because they are used to guide and assess the design of systems in the context of normal and emergency conditions. Lastly, the applicability of personal protective equipment and other mitigative measures during emergency conditions is described to explain how the NRC has traditionally not credited these measures during safety evaluations of control room designs; however, their use can be expected during emergency conditions.

Radiation protection concerns the protection of individuals, their progeny, and humankind, while still allowing necessary activities from which radiation exposure might result. The aim of radiation protection is generally to prevent detrimental nonstochastic, or deterministic, effects (e.g., cataracts, skin reddening, or erythema) and to limit the probability of stochastic effects (i.e., cancer) to levels deemed to be acceptable. Nonstochastic effects are prevented by setting dose equivalent limits at sufficiently low values so that these effects are not experienced as a result of exposures within the limits. Stochastic effects are limited by keeping all justifiable exposures as low as is reasonably achievable (ALARA), economic and social factors being taken into account, subject always to the boundary condition that the applicable dose equivalent limits shall not be exceeded.

An additional aim of radiation protection is to ensure that practices involving radiation exposure are justified with regard to the benefit of the activity compared to the risks incurred by the workers who provide the benefit. Therefore, when developing the numerical occupational dose limit recommendations that apply to stochastic exposure and upon which the NRC regulations are based, the International Commission on Radiological Protection (ICRP) ensured that the risk of fatality from stochastic effects of radiation on the population of workers was comparable to the risk of fatalities to workers in other industries considered safe. This approach led to conservative dose limitations that have served the radiation worker community well but may not have been appropriate to apply as design criteria that encompass expected system performance during highly unlikely emergency situations at power plants.

The standards set forth in 10 CFR Part 20, “Standards for Protection Against Radiation” [Ref. 20], are based in part on the recommendations of the ICRP and its U.S. counterpart, the NCRP. In 1977, with Publication 26, “Recommendations of the ICRP” (ICRP 26) [Ref. 21], the ICRP issued revised recommendations for a system of radiation dose limitations. The NRC adopted this system on May 21, 1991, in its amendment of 10 CFR Part 20. As such, 10 CFR Part 20 puts into practice recommendations from ICRP 26 and certain subsequent ICRP publications. As discussed in the *Federal Register* (FR) (56 FR 23360; May 21, 1991) [Ref. 22]—

> In adopting the basic tenets of the ICRP system of dose limitation, the Nuclear Regulatory Commission recognizes that, when application of the dose limits is combined with the principle of keeping all radiation exposures “as low as is reasonably achievable,” the degree of protection could be significantly greater

than from relying upon the dose limits alone.

The regulations in 10 CFR Part 20 apply these standards to all exposure situations—normal and abnormal—but an explicit exemption is also provided if compliance would limit actions that may be necessary to protect health and safety.

The ICRP 26 system of dose limitation has the following objectives:

- No practice shall be adopted unless its introduction produces a positive net benefit.
- All exposures shall be kept ALARA, economic and social factors being taken into account.
- The dose equivalent to individuals shall not exceed the limits recommended for the appropriate circumstances by the Commission.

To achieve these objectives, this system of dose limitations ensures that no source of exposure is unjustified in relation to its benefits or those of any available alternative, that any necessary exposures are kept ALARA, and that the dose equivalents received do not exceed certain specified limits. As such, any necessary exposures are kept ALARA and that the dose equivalents received do not exceed certain specified limits.

Occupational Control Room Doses

The NRC's current regulatory approach to control room operator radiation exposure conservatively adopts the tenets of international and national radiation protection standards and recommendations. As discussed above, this approach is provided in GDC 19; 10 CFR 50.67, "Accident source term"; 10 CFR Part 20; 10 CFR 50.47(b)(11); and, by reference, the U.S. Environmental Protection Agency (EPA) "PAG Manual: Protective Action Guides and Planning Guidance for Radiological Incidents," issued January 2017 [Ref. 23].

ICRP 26, Section G, "Application to the Different Types of Exposure," provides recommendations for occupational exposure. These recommendations state in part that as far as is reasonably practicable, the methods for restricting occupational exposure should be applied to the source of radiation and to features of the workplace. The use of personal protective equipment should, in general, supplement these more fundamental provisions. Therefore, emphasis should be on intrinsic safety in the workplace (e.g., physical design and operating characteristics of systems) and only secondarily on protection that depends on a worker's own actions. However, under abnormal or emergency situations, arrangements are made not only with respect to the detection and assessment of dose or intake, but also with respect to the mitigating interventions that may have to be applied to further protect workers (e.g., personal protective equipment, administration of prophylactic drugs, and evacuation).

It is significant to note that the contents of Appendix A to 10 CFR Part 50 are design criteria and not operational limits. Events and situations not addressed in the facility's design basis could in fact result in conditions for which the design might not provide the reasonable assurance sought. For example, multiple failures that are not the result of a common mode failure are not required to be addressed in the design basis of the control room. Should such multiple failures occur, the performance of the SSCs may not be adequate and compensatory plant operations

might be necessary. The NRC's focus on defense in depth provides assurance that even if these beyond-design-basis conditions occur, the plant design will mitigate the risk to occupational workers and public health and safety.

The standards for protection against radiation established in 10 CFR Part 20 are generally consistent with the recommendations of ICRP 26, the later ICRP recommendations from ICRP Publication 60, "1990 Recommendations of the International Commission on Radiological Protection," issued 1991 (ICRP 60) [Ref. 24], and the ICRP Publication 103, "The 2007 Recommendations of the International Commission on Radiological Protection," issued 2007 (ICRP 103) [Ref. 25]. The rule applies the ICRP 26 recommendations to all exposure situations—normal and abnormal—but also provides an explicit exemption for cases in which compliance would limit actions that may be necessary to protect health and safety. In an emergency situation, the continued actions of the control room operators are fundamental to protecting the health and safety of the public and other workers at the facility. Thus, if the event should result in conditions beyond the design basis of the control room habitability systems, thereby causing actual radiation exposures that exceed the normal occupational limits, access and occupancy of the control room may continue. There are, however, additional regulatory provisions that bear on the control of occupational exposures during emergencies.

The NRC has established emergency planning regulations in Appendix E, "Emergency Planning and Preparedness for Production and Utilization Facilities," to 10 CFR Part 50, and planning standards for nuclear power reactors in 10 CFR 50.47, "Emergency plans," for the purpose of providing reasonable assurance that adequate protective measures can and will be taken in the event of a radiological emergency. The regulation at 10 CFR 50.47(b)(11) addresses control of radiological exposures in an emergency and states that the means for controlling radiological exposures shall include exposure guidelines consistent with EPA Emergency Worker and Lifesaving Activity Protection Action Guides. The events that could result in control room radiation exposures comparable to the 10 CFR Part 20 normal occupational exposure limit of 0.05 Sv (5 rem) TEDE would result in the activation of the facility's emergency response plan and the emergency response organization. Regulatory Guide 1.101, "Emergency Response Planning and Preparedness for Nuclear Power Reactors," Revision 6, issued June 2021 [Ref. 26], endorses NUREG-0654/FEMA-REP-1, "Criteria for Preparation and Evaluation of Radiological Emergency Response Plans and Preparedness in Support of Nuclear Power Plants," Revision 2, issued December 2019 [Ref. 27]. NUREG-0654/FEMA-REP-1 provides specific acceptance criteria for complying with the standards set forth in 10 CFR 50.47, which designates an on-shift emergency coordinator. The on-shift emergency coordinator has the authority and responsibility to immediately and unilaterally initiate any emergency actions. These emergency actions include establishing higher exposure limits for control room operators if necessary to provide public health and safety. The emergency coordinator can also authorize issuing potassium-iodide tablets for thyroid protection or use of emergency respiratory protection equipment.

This radiation protection framework is consistent with the ICRP recommendations as follows:

ICRP 26

(paragraph 113) Situations may occur infrequently during normal operations when it may be necessary to permit a few workers to receive dose equivalents in excess of the recommended limits. In such circumstances external exposures or

intakes of radioactive material may be permitted provided the dose-equivalent commitment does not exceed twice the relevant annual limit in any single event, and, in a lifetime, five times this limit. The Commission wishes to emphasize that external exposures or intakes of this magnitude are only justified when alternative techniques, which do not involve such exposure of workers, are either unavailable or impracticable (see also paragraph 171).

(paragraph 114) Planned special exposures should not be permitted if the worker has previously received abnormal exposures resulting in dose equivalents in excess of five times the relevant annual limit. Planned special exposures should not be permitted for women of reproductive capacity. Dose equivalents resulting from planned special exposures should be recorded with those from usual exposures, but any excess over the limits recommended in paragraphs 103 *et seq.* should not by itself constitute a reason for excluding a worker from his usual occupation. (Accidental and emergency exposures are discussed in section G, paragraph 160).

(paragraph 167) As far as is reasonably practicable, the arrangements for restricting occupational exposure should be those applied to the source of radiation and to features of the workplace. The use of personal protective equipment should in general be supplementary to these more fundamental provisions. The emphasis should thus be on intrinsic safety in the workplace and only secondarily on protection that depends on the worker's own actions.

(paragraph 169) External exposure may be restricted by the use of shielding, distance and limitation of time of exposure. Shielding produces intrinsically safe conditions in the workplace. Distance and limitation of time of exposure require the careful training and supervision of workers. Complete protection is afforded by the use of "closed" installations providing virtually complete shielding for the radiation source and effectively preventing access. However, the failure of such equipment as interlock systems may cause excessive exposure. Operating procedures should therefore include routine checks of such systems.

(paragraph 189) The emergency plans (which should, as far as practicable, be drawn up in advance) should have three clearly distinguished objectives. The first is to restrict exposures as far as reasonably achievable and, in particular, to attempt to avoid exposures above the dose-equivalent limits. The second is to bring the situation back under control, and the third is to obtain information for assessing the causes and consequences of the event.

(paragraph 191) During the immediate course of a serious incident, urgent action to save life, to prevent injuries, or to prevent a substantial increase in the scale of the incident, may require that some workers be exposed in excess of the limits….

(paragraph 192) Once the initial event has been brought under control, there remains the problem of remedial work. It will usually be appropriate to carry this out while maintaining compliance with the Commission's [i.e., the ICRP's] recommended limits but, exceptionally, there may be situations which the use of

the limits would involve excessive expense or an excessive involvement of people and time. Consideration should then be given to the appropriateness of authorizing a planned special exposure for a limited number of individuals to carry out various essential operations, leaving the remainder to be done in compliance with the limits.

ICRP 60

(paragraph 195) The initial treatment of potential exposures should form part of the system of protection applied to practices, but it should be recognised that the exposures, if they occur, may lead to intervention. At this stage, there should be two objectives, prevention and mitigation. Prevention is the reduction of the probability of the sequences of events that may cause or increase radiation exposures. It involves maintaining the reliability of all the operating and safety systems and of the associated working procedures. Mitigation is the limitation and reduction of the exposures if any of these sequences do occur. It involves the use of engineered safety features and operational procedures to control each sequence of events with the aim of limiting its consequences, should it occur. The arrangements for mitigation should not be restricted to plans for intervention. A great deal can be accomplished at the stages of design and operation to reduce the consequences of accident sequences so that intervention may not become necessary. It is difficult to compare, and to combine, the benefit of a reduction in probability (prevention) with that of a reduction in dose (mitigation) because a reduction in probability by a factor is not usually seen as equivalent to a reduction in dose by the same factor.

(paragraph S49) The benefit of a particular protective action within a programme of intervention should be judged on the basis of the reduction in dose achieved or expected by that specific protective action, i.e. the dose averted. Thus, each protective action has to be considered on its own merits. In addition, however, the doses that would be incurred via all the relevant pathways of exposure, some subject to protective actions and some not, should be assessed. If the total dose in some individuals is so high as to be unacceptable even in an emergency, the feasibility of additional protective actions influencing the major contributions to the total dose should be urgently reviewed. Doses causing serious deterministic effects, or a high probability of stochastic effects would call for such a review.

(paragraph S50) Occupational exposures of emergency teams during emergency and remedial action can be limited by operational controls. Some relaxation of the controls for normal situations can be permitted in serious accidents without lowering the long-term level of protection. This relaxation should not permit the exposures in the control of the accident and in the immediate and urgent remedial work to give effective doses of more than about 0.5 Sv [50 rem] except for life-saving actions, which can rarely be limited by dosimetric assessments. The equivalent dose to skin should not be allowed to exceed about 5 Sv [500 rem]. Once the immediate emergency is under control, remedial work should be treated as part of the occupational exposure incurred in a practice.

ICRP 103

(paragraph u) Emergency exposure situations include consideration of emergency preparedness and emergency response. Emergency preparedness should include planning for the implementation of optimised protection strategies which have the purpose of reducing exposures, should the emergency occur, to below the selected value of the reference level. During emergency response, the reference level would act as a benchmark for evaluating the effectiveness of protective actions and as one input into the need for establishing further actions.

Control Room Design Criteria

The control room design criteria, as described in GDC 19, call for the plant design to incorporate radiation protection features that, in the event of an emergency, would maintain the radiation exposure of control room personnel to a level equal to their normal occupational exposure limits. It is generally understood that an objective of the criteria is to ensure that the design of the control room and its habitability systems was such that a "shirt-sleeved" environment was provided for the control room operators. Exceeding the control room design criteria numerical value of 0.05 Sv (5 rem) TEDE would not impose an immediate health effect or even require an evacuation requirement on the control room operators. However, having a numerical criterion for designers to reference when accounting for accidents in their designs is necessary and consistent with the ICRP. Though setting the criteria to the normal occupational dose limits to assess plant performance during emergency conditions may mask its intended purposes when also assessing other regulations. To provide context, we highlight a parallel between the control room design criteria and the occupational dose limits in 10 CFR 20.1206, "Planned special exposures." As long as licensees meet certain criteria, 10 CFR Part 20 allows planned special exposures up to twice the annual occupational dose limits provided that lifetime exposure of 0.25 Sv (25 rem) TEDE is not exceeded. As discussed in 56 FR 23372, planned special exposures were retained in the amended 10 CFR Part 20 in part to address the fact that under the new system of dose limitation workers would no longer have a lifetime dose limit, or "dose bank," equaling five times the quantity of the age of the worker minus 18, or 5(N−18). While the use of planned special exposures was predicted to be infrequent, it was expected that they would be used if the elimination of the lifetime dose limits might "create a severe handicap to the licensee's operations." Therefore, the Commission concluded that an infrequent exposure of workers up to twice the occupational dose limit was adequately protective of radiation workers. Now, the control room design criteria are applicable to a low-frequency event, whereas the planned special exposure is designed for a more likely routine radiological exposure event. Based on a potential radiological risk each rule is intending to protect against, the applicable dose constraints for less likely emergency events should be aligned (higher) than the dose constraints for the lower frequency events (planned special exposures) at 0.10 sievert (Sv) (10 roentgen equivalent man (rem)) as well as routine occupational exposures 0.05 Sv (5 rem).

ICRP 26

(paragraph 190) Although, by their nature, accidental exposures are not subject to control, their magnitude can to some extent be limited by intervention, especially if attention has been paid to this possibility during the design of installations and equipment and the preparation of operating instructions.

ICRP 60

(paragraph 224) Occupational exposures directly due to an accident can be limited only by the design of the plant and its protective features and by the provision of emergency procedures. Ideally, the aim should be to keep the doses within those permitted in normal conditions, but, while this is usually possible, it may not always be so in serious accidents.

ICRP 103

(paragraph r) The process of planning protection in planned exposure situations should include consideration of deviations from normal operating procedures including accidents and malicious events. ... Potential exposures are not planned but they can be anticipated. The designer and the user of a source must therefore take actions to reduce the likelihood of a potential exposure happening, such as assessing the probability of an event and introducing engineering safeguards commensurate to this probability.

Performance-Based Regulations, Design-Basis Accidents, and Use of Personal Protective Equipment

The control room design criteria regulations are "performance based," requiring a licensee or applicant to provide a control room habitability design that meets a specified dose-based criterion. Specifically, they establish performance requirements for control room habitability systems that would be called upon in a DBA. This is directly responsive to the ICRP recommendations to emphasize intrinsic safety features. These systems serve the function of mitigation, thereby minimizing the need for intervention, which might involve evacuation, administration of prophylactic drugs, or use of personal protective equipment that could impair the operators' ability to perform the actions necessary to provide adequate public health and safety.[3] To demonstrate compliance, licensees perform traditional deterministic DBA radiological consequence analyses using "regulatory source terms" which are reviewed and approved by the staff. Performance-based regulations, such as 10 CFR 50.67(b)(2)(iii) and GDC 19, do not provide prescriptive methodologies to determine the regulations are met and therefore do not require licensees to use specific designs or methodologies to comply with the regulations. As such, NRC RGs and standard review plans provide acceptable methodologies that licensees can use to perform the analyses, which are then incorporated, as appropriate, into the licensing basis for the licensee's facility. In general, the staff has generally not accepted, except in interim situations, personal protective measures such as respiratory protection or prophylactic drugs which is consistent with the ICRP recommendations.

The licensing process is based on the concept of defense in depth, in which power plant design, operation, siting, and emergency planning comprise independent layers of nuclear safety. This approach encourages nuclear plant designers to incorporate several lines of defense in order to maintain the effectiveness of physical barriers between radiation sources and materials from workers, members of the public, and the environment in operational states and, for some

[3] This is also consistent with 10 CFR 20.1701, "Use of process or other engineering controls" [Ref. 28], which requires the licensee to use, to the extent practical, process or other engineering controls (e.g., containment, decontamination, or ventilation) to control the concentrations of radioactive materials in air.

barriers, in accident conditions. The approach uses DBAs with regulatory source terms to compute radiological consequences when assessing the effectiveness of each line of defense. As such, the DBAs establish and confirm the design basis of the nuclear facility, including its safety-related SSCs and items important to safety, ensuring that the plant design meets the safety and numerical radiological criteria set forth in regulations and subsequent guidance. Due to the conservative, deterministic nature of the DBA analyses, there is a margin of safety such that control room design may be adequate for many events beyond the design basis. However, it remains possible that actual radiation exposures from beyond-design-basis events, or those resulting from multiple failures of the control room habitability systems coincident with a DBA, could exceed the design criteria. In such an event, the radiation exposures are still subject to 10 CFR Part 20 first and then the facility's emergency plan, which would use personal protective equipment, if necessary, supplementary to these more fundamental design provisions. Under emergency conditions, both maintain radiation exposures to be ALARA and, to the extent practicable, limited to normal occupational levels. This is consistent with the ICRP 26, ICRP 60, and ICRP 103 recommendations.

ICRP 26

(paragraph 167) As far as is reasonably practicable, the arrangements for restricting occupational exposure should be applied to the source of radiation and to features of the workplace. The use of personal protective equipment should in general be supplementary to these more fundamental provisions. The emphasis should thus be on intrinsic safety in the workplace and only secondarily on protection that depends on the worker's own actions.

ICRP 60

(paragraph 195) The initial treatment of potential exposures should form part of the system of protection applied to practices, but it should be recognized that the exposures, if they occur, may lead to intervention. At this stage there should be two objectives, prevention and mitigation. Prevention is the reduction of the probability of the sequences of events that may cause or increase radiation exposures. It involves maintaining the reliability of all of the operating and safety systems and of the associated working procedures. Mitigation is the limitation and reduction of the exposures if any of these sequences do occur. It involves the use of engineered safety features and operational procedures to control each sequence of events with the aim of limiting its consequences, should it occur. The arrangement for mitigation should not be restricted to plans of intervention. A great deal can be accomplished at the stages of design and operation to reduce the consequences of accident sequences so that intervention may not become necessary.

ICRP 103

(paragraph t) Emphasis on optimisation using reference levels in emergency and existing exposure situations focuses attention on the residual level of dose remaining after implementation of protection strategies. This residual dose should be below the reference level, which represents the total residual dose as

a result of an emergency, or in an existing situation, that the regulator would plan not to exceed. These exposure situations often involve multiple exposure pathways which means that protection strategies involving a number of different protective actions will have to be considered. The process of optimisation will however continue to use the dose averted by specific countermeasures as an important input into the development of optimized strategies.

Item 3: Provide an annotated bibliography of radiation protection recommendations for workers during emergency conditions from national and international organizations responsible for making recommendations for radiation protection standards.

The staff reviewed a number of source materials to understand the current state of knowledge and organizations' recommendations for protecting radiation workers from radiation under accident conditions. The purpose of this review was to determine whether reexamining the technical basis for the control room design criteria would be warranted in light of this increased enrichment rulemaking. The staff also reviewed other NRC regulations and national and international organizations responsible for making recommendations for radiation protection standards. The purpose was to understand whether the currently selected numerical value of 0.05 Sv (5 rem) TEDE fits within the range of values used for worker protection during emergency conditions:

- At the time that GDC 19 was published in 1971, 10 CFR Part 20 limited occupational radiation exposure to 0.03 Sv (3 rem) whole body dose per calendar quarter, provided the total lifetime dose was verified not to exceed 0.05 Sv (5 rem) times the individual's age in years minus 18 (i.e., 5(N−18)). It was possible to receive a radiation exposure of up to 0.12 Sv (12 rem) in a given year.

- The current annual limit on occupational radiation dose exposure in 10 CFR 20.1201, "Occupational Dose Limits for adults," is 0.05 Sv (5 rem) TEDE. Under 10 CFR 20.1201, it is possible to receive occupational radiation exposure of up to 0.10 Sv (10 rem) TEDE over a 12-month period straddling two calendar years.

- The current 10 CFR 20.1206 on planned special exposures also permits an adult worker to receive doses in addition to and accounted for separately from the doses received under the limits specified in 10 CFR 20.1201 of five times the annual dose limits during the individual's lifetime, not to accumulate faster than 0.05 Sv (5 rem) TEDE in any one year. It is possible to receive radiation exposure of up to 0.10 Sv (10 rem) TEDE within a single calendar year period.

- The EPA exposure guidelines found in the PAG Manual recommend that doses received under emergency conditions should be maintained ALARA and, to the extent practicable, limited to 0.05 Sv (5 rem). The guideline for actions to protect valuable property is 0.10 Sv (10 rem) where a lower dose is not practicable, the guideline for actions to save a life or to protect large populations is 0.25 Sv (25 rem) where a lower dose is not practicable, and exposures greater than 0.25 Sv (25 rem) may be appropriate for lifesaving or protecting large populations if the workers are volunteers who are fully aware of the risks involved.

- Health Physics Society Position Statement PS010-4, “Radiation Risk in Perspective,” issued January 2020 [Ref. 29], states that substantial and convincing scientific data show evidence of health effects following high-dose exposures (i.e., many multiples of natural background). However, below levels of about 100 mSv (10 rem) above background from all sources combined, the observed radiation effects in people are not statistically different from zero.

- ICRP Publication 109, “Application of the Commission’s Recommendations for the Protection of People in Emergency Exposure Situations,” issued 2009 [Ref. 30], specifies a range of 0.02–0.10 Sv (2–10 rem) acute for emergency exposure situations. For doses above 0.10 Sv (10 rem), protective measures should be justified.

- International Atomic Energy Agency guidance [Ref. 31] for emergency workers specify a range of 0.05–1 Sv (5-100 rem), depending on the severity of the actions needed.

- NCRP Report No. 180, “Management of Exposure to Ionizing Radiation: Radiation Protection Guidance for the United States,” issued 2018 [Ref. 32], specifies that (1) during lifesaving activities or actions to prevent a catastrophic situation, which includes other urgent rescue activities, 0.5 gray (Gy) cumulative whole-body absorbed dose (50 rad) should be implemented at the command level, and (2) for other emergency activities, including extended activities following initial lifesaving, rescue, and damage control response, an effective dose to emergency workers should not exceed 0.10 Sv (10 rem).

In summary, there is a range of regulatory-based and international and national organization-based recommendations for radiation exposures for radiation workers under normal and emergency conditions. According to the regulations, occupational workers can receive up to 0.10 Sv (10 rem) occupationally during a 12-month period under a special circumstance within a calendar year. Intergovernmental and national and international organizations recommend emergency exposure dose limitations up to 0.25 Sv (25 rem) TEDE or 0.5 Gy (50 rad) whole body and up to 1 Gy (100 rad) for emergency responders. As such, the control room design criteria intended to assess the acceptability of a given control room design is on the lower end of a range of recommended values for emergency response planning to protect against actual incurred radiation exposure during an event.

Item 4: Provide an assessment of the identified design criteria to contemporary radiological health effects.

This section provides the staff’s assessment of the control room design criteria, with a numerical value of 0.05 Sv (5 rem), as compared to information found in professional literature, as well as recommendations regarding modern health physics knowledge, radiation protection standards, and radiation epidemiology knowledge.

As discussed above, the control room design criteria were developed and issued to establish minimum necessary design, fabrication, construction, testing, and performance requirements for SSCs that provide reasonable assurance that a facility can be operated without undue risk to the health and safety of the occupational workers and of the public. The design criteria are not operational limits, and they do not represent actual exposures received during normal operation

or an emergency condition. Instead, these criteria are “figures-of-merit” that are compared against the results of traditional deterministic radiological consequence analyses using a DBA source term to judge the acceptability of the control room design.

In the context of the increased enrichment rulemaking, the question arises as to whether the current control room design criteria could be increased to a higher, yet still safe, performance level when considering contemporary understandings of radiological health effects.

With sufficient dose, the biological health effects of radiation exposure manifest in one of two ways: stochastic or deterministic. Stochastic health effects occur randomly, and the probability of the effects occurring, rather than their severity, is assumed to be a linear function of dose without threshold. Doses that contribute to stochastic effects can be accumulated over long periods of time, from years to decades. Cancer incidence is an example of a stochastic effect. Conversely, for deterministic health effects, the severity varies with the dose for which an empirically derived threshold is established. Acute radiation syndrome is a significant deterministic effect that can pose significant safety issues during emergency response because it can significantly hamper the effectiveness of control room operators. Data on the various forms of acute radiation syndrome have been collected from many sources. Animal experiences provide the bulk of the data and results. At the human level, data have been drawn from experiences in radiation therapy and studies from a number of nuclear-related accidents.

There are two radiation units that assess either stochastic effects or deterministic radiation health effects. The first is the Sv (or rem) TEDE, which is the sum of the effective dose equivalent for external exposures and the committed effective dose equivalent for internal exposures. The Sv (rem) TEDE adjusts the dose equivalent radiation exposure using a tissue weighting factor that represents the proportion of the risk of stochastic effects resulting from irradiation of an organ, or tissue, to the total risk of stochastic effects when the whole body is irradiated uniformly. The committed effective dose equivalent is a 50-year committed “dose” based on an initial intake of radioactive material used to estimate the stochastic health effect of cancer mortality. In other words, the dose is assigned to the first year of intake to estimate the increased probability of cancer induced fatality after 50 years. The second radiation unit is the Gy, or rad, which is used to measure the amount of energy deposited in tissue. Typically, radiation exposures that cause deterministic health effects are measured in Gy (rad).

Exposure of the whole body to a large dose over a short period of time (<1 hour) may cause effects due to the sensitivity of cells in the body. Acute radiation syndrome can result following significant whole-body exposures in a short time. Effects may include blood changes, nausea, vomiting, diarrhea, and central nervous system damage. Hematopoietic syndrome is observed by a decrease in blood cell count at doses of about 1 Gy (100 rad). Gastrointestinal syndrome from a dose of about 5 Gy (500 rad) will result in nausea, vomiting, and diarrhea. Central nervous system syndrome, observed at about a dose of 20 Gy (2,000 rad), will affect the muscle and brain function of the central nervous system. The dose which is lethal to 50 percent of the people within 60 days if medical treatment is not provided is called the “LD 50/60.” The LD 50/60 dose is approximately 3–5 Gy (300–500 rads; ~90 times the annual dose limit for routine occupational exposure) in an hour to an average adult. If received within a short time period (e.g., a few hours), an LD 5-/60 dose will cause vomiting and diarrhea within a few hours and loss of hair, fever, and weight loss within a few weeks. These effects would not occur if the

same dose were accumulated gradually over many weeks or months, such as during radiation therapy treatments.

The radiation risk of cancer mortality is assessed by first quantifying the "baseline" risk of cancer death within a given population. For the United States, this is approximately 20 percent. Therefore, a population of 10,000 people would develop approximately 2,000 (20 percent of 10,000) fatal cancers due to the "natural incidence" of cancer. Exposure to radiation dose of up to 0.01 Sv (1 rem) may increase the overall risk to 20 percent + 0.05 percent = 20.05 percent. Collective dose to a population of 10,000 person-rem (0.01 Sv (1 rem) to each person in a population of 10,000) may result in five additional cancer fatalities, besides the 2,000 that will occur naturally. That is, there would be 2,005 fatal cancers, rather than 2,000. However, the natural incidence of fatal cancers is not precisely 2,000, and it is not possible to unequivocally distinguish these additional cases from those occurring naturally. As a consequence of collective dose in a lifetime, approximately 42 out of 100 people will be diagnosed with cancer from causes unrelated to radiation. As previously mentioned, about 20 percent of the population dies from some form of cancer. So, of the 42 percent of people who develop cancer, half will survive. If 100 people received a dose of 0.1 Sv (10 rem), it is estimated that there will be one additional cancer incidence in this group for a total of 43 cancer incidents. More information concerning risk from ionizing radiation is available in Regulatory Guide 8.29, "Instruction Concerning Risks from Occupational Radiation Exposure," Revision 1, issued February 1996 [Ref. 33].

In summary, ionizing radiation can cause biological effects. While the biological effects from ionizing radiation are not unique to radiation, it is important to limit the amount of radiation dose received by an individual. The probability of stochastic effects of radiation, such as causing cancer, increase with radiation dose. The limitation of stochastic effects is achieved by keeping all justifiable exposures ALARA, given economic and social factors being considered, subject always to the boundary condition that the appropriate dose limit is not exceeded. Deterministic effects have a threshold dose that must be exceeded for the effects to occur, and the severity of these effects also increases with dose. The prevention of deterministic effects is achieved by setting dose equivalent limits at sufficiently low values so that no threshold dose would be reached, even following exposure for the whole of a lifetime or for the total period of an individual's working life. As discussed above, the NRC has set dose limits to minimize stochastic effects and to avoid deterministic effects. Therefore, the aim of the NRCs radiation protection standards is to prevent detrimental deterministic effects and to limit the probability of stochastic effects to levels deemed to be acceptable.

The control room design criteria radiation unit of "rem TEDE" does not technically "match" the expected measured deterministic health effects expected from a reactor accident. However, the 10 CFR Part 20 annual occupational exposure limit of 0.05 Sv (5 rem) TEDE is set sufficiently low that no deterministic threshold dose would be reached. This occupational exposure limit is applicable to both normal and emergency conditions. The review of regulations pertaining to occupational workers and radiation protection recommendations for workers during emergency conditions identified a range of recommended acceptable criteria. These criteria would continue to provide reasonable assurance that the facility can be operated during an emergency without undue risk to public health and safety as they are set sufficiently low to protect against deterministic health effects that would cause operator impartment.

REFERENCES

1. U.S. Nuclear Regulatory Commission (NRC), "Assessment of Radiation Protection Recommendations for Emergency Workers," Form 843, Informal Assistance Request NRR-2022-019, August 26, 2022, Agencywide Documents Access and Management System (ADAMS) Accession No. ML22259A017.

2. Nuclear Energy Institute, "The Economic Benefits and Challenges with Utilizing Increased Enrichment and Fuel Burnup for Light-Water Reactors," February 2019, ML21259A191.

3. NRC, "Project Plan to Prepare the U.S. Nuclear Regulatory Commission for Efficient Licensing of Accident Tolerant Fuels," Version 1.2, September 2021, ML21243A298.

4. *U.S. Code of Federal Regulations*, "Criticality accident requirements," Section 50.68, Chapter I, Title 10, "Energy." (available at https://www.nrc.gov/reading-rm/doc-collections/cfr/part050/part050-0068.html)

5. NRC, "Rulemaking Plan on Use of Increased Enrichment of Conventional and Accident Tolerant Fuel Designs for Light-Water Reactors," SECY-21-0109, December 20, 2021, ML21232A237.

6. NRC, "Staff Requirements—SECY-21-0109—Rulemaking Plan on Use of Increased Enrichment of Conventional and Accident Tolerant Fuel Designs for Light-Water Reactors," SRM-SECY-21-0109, March 16, 2022, ML22075A103.

7. *U.S. Code of Federal Regulations*, "Accident source term," Section 50.67, Chapter I, Title 10, "Energy." (available at https://www.nrc.gov/reading-rm/doc-collections/cfr/part050/part050-0067.html)

8. *U.S. Code of Federal Regulations*, "Control room," General Design Criterion 19, "General Design Criteria for Nuclear Power Plants," Appendix A, Part 50, Chapter I, Title 10, "Energy." (available at https://www.nrc.gov/reading-rm/doc-collections/cfr/part050/part050-appa.html#4_appa)

9. U.S. Nuclear Regulatory Commission, "Be riskSMART—Guidance for Integrating Risk Insights into NRC Decisions," NUREG/KM-0016, March 2021, ML21071A238.

10. *U.S. Code of Federal Regulations*, "Contents of applications; technical information," Section 50.34, Chapter I, Title 10, "Energy." (available at https://www.nrc.gov/reading-rm/doc-collections/cfr/part050/part050-0034.html)

11. *U.S. Code of Federal Regulations*, "Contents of applications; technical information," Section 52.17, Chapter I, Title 10, "Energy." (available at https://www.nrc.gov/reading-rm/doc-collections/cfr/part052/part052-0017.html)

12. *U.S. Code of Federal Regulations*, "Contents of applications; technical information," Section 52.47, Chapter I, Title 10, "Energy." (available at https://www.nrc.gov/reading-rm/doc-collections/cfr/part052/part052-0047.html)

13. *U.S. Code of Federal Regulations*, "Contents of applications; technical information," Section 52.79, Chapter I, Title 10, "Energy." (available at https://www.nrc.gov/reading-rm/doc-collections/cfr/part052/part052-0079.html)

14. *U.S. Code of Federal Regulations*, "Contents of applications; technical information," Section 52.137, Chapter I, Title 10, "Energy." (available at https://www.nrc.gov/reading-rm/doc-collections/cfr/part052/part052-0137.html)

15. *U.S. Code of Federal Regulations*, "Contents of applications; technical information in final safety analysis report," Section 52.157, Chapter I, Title 10, "Energy." (available at https://www.nrc.gov/reading-rm/doc-collections/cfr/part052/part052-0157.html)

16. *U.S. Code of Federal Regulations*, "Determination of exclusion area, low population zone, and population center distance," Section 100.11, Chapter I, Title 10, "Energy." (available at https://www.nrc.gov/reading-rm/doc-collections/cfr/part100/part100-0011.html)

17. *U.S. Code of Federal Regulations*, "Planned special exposures," Section 20.1206, "Occupational Dose Limits," Subpart C, Chapter I, Title 10, "Energy." (available at https://www.nrc.gov/reading-rm/doc-collections/cfr/part020/part020-1206.html)

18. *U.S. Code of Federal Regulations*, "Occupational dose limits for adults," Section 20.1201, "Occupational Dose Limits," Subpart C, Chapter I, Title 10, "Energy." (available at https://www.nrc.gov/reading-rm/doc-collections/cfr/part020/part020-1201.html)

19. U.S. National Bureau of Standards, "Maximum Permissible Body Burdens and Maximum Permissible Concentrations of Radionuclides in Air and in Water for Occupational Exposure," Handbook 69, June 5, 1959 (available at https://nvlpubs.nist.gov/nistpubs/Legacy/hb/nbshandbook69.pdf).

20. *U.S. Code of Federal Regulations*, "Standards for Protection Against Radiation," Part 20, Chapter I, Title 10, "Energy." (available at https://www.nrc.gov/reading-rm/doc-collections/cfr/part020/index.html)

21. International Commission on Radiological Protection (ICRP), "Recommendations of the ICRP," *Annals of the ICRP* 1(3), ICRP Publication 26, 1977 (available at https://www.icrp.org/publication.asp?id=ICRP%20Publication%2026).

22. NRC, "Standards for Protection against Radiation," *Federal Register*, Vol. 56, No. 98, pp. 23360–23401, May 21, 1991. (available at https://archives.federalregister.gov/issue_slice/1991/5/21/23349-23474.pdf#page=12)

23. U.S. Environmental Protection Agency, "PAG Manual: Protective Action Guides and Planning Guidance for Radiological Incidents," EPA-400/R-17/001, January 2017 (available at https://www.epa.gov/radiation/protective-action-guides-pags#pagmanual).

24. ICRP, "1990 Recommendations of the International Commission on Radiological Protection," *Annals of the ICRP* 21(1–3), ICRP Publication 60 (User's Edition), 1991

(available at https://www.icrp.org/publication.asp?id=ICRP%20Publication%2060%20(Users%20Edition)).

25. ICRP, "The 2007 Recommendations of the International Commission on Radiological Protection," *Annals of the ICRP* 37(2–4), ICRP Publication 103, 2007 (available at https://www.icrp.org/publication.asp?id=ICRP%20Publication%20103).

26. NRC, "Emergency Response Planning and Preparedness for Nuclear Power Reactors," Regulatory Guide 1.101, Revision 6, June 2021, ML21111A090.

27. NRC and Federal Emergency Management Agency, "Criteria for Preparation and Evaluation of Radiological Emergency Response Plans and Preparedness in Support of Nuclear Power Plants: Final Report," NUREG-0654/FEMA-REP-1, Rev. 2, December 2019, ML19347D139.

28. *U.S. Code of Federal Regulations*, "Use of process or other engineering controls," Section 20.1701, "Respiratory Protection and Controls to Restrict Internal Exposure in Restricted Areas," Subpart H, Chapter I, Title 10, "Energy." (available at https://www.nrc.gov/reading-rm/doc-collections/cfr/part020/part020-1701.html)

29. Health Physics Society, "Position Statement of the Health Physics Society PS010-4: Radiation Risk in Perspective," *Health Physics* 118(1), pp. 79–80, January 2020. (available at https://journals.lww.com/health-physics/fulltext/2020/01000/position_statement_of_the_health_physics_society.8.aspx)

30. ICRP, "Application of the Commission's Recommendations for the Protection of People in Emergency Exposure Situations," *Annals of the ICRP* 39(1), ICRP Publication 109, 2009 (available at https://www.icrp.org/publication.asp?id=icrp%20publication%20109).

31. International Atomic Energy Agency, "Portable Digital Assistant for First Responders to a Radiological Emergency: Emergency worker turn-back dose guidance," n.d. (available at https://www-pub.iaea.org/mtcd/publications/pdf/epr-first_res-pda/html/ti2-turn-back-dose.htm#ftn.10).

32. National Council on Radiation Protection and Measurements (NCRP), "Management of Exposure to Ionizing Radiation: Radiation Protection Guidance for the United States," NCRP Report No. 180, 2018 (available at https://ncrponline.org/shop/reports/report-no-180-management-of-exposure-to-ionizing-radiation-radiation-protection-guidance-for-the-united-states-2018-2018/).

33. NRC, "Instruction Concerning Risks from Occupational Radiation Exposure," Regulatory Guide 8.29, Rev. 1, February 1996, ML003739438.