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Revision 0

Reevaluation of Radiation Protection Standards for Workers and the Public Based on Current Scientific Evidence

JULY 2025

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ABSTRACT

Recent executive orders to "Usher in a Nuclear Renaissance," coupled with the global pledge to triple nuclear energy capacity by 2050, underscore nuclear energy's importance to national security and economic prosperity. This renewed interest has prompted efforts to spur nuclear-energy deployment, including assessing factors impeding it. One issue that has been identified as adding to the cost of nuclear energy is excessively conservative requirements, including those related to radiation protection. This technical review examines current radiation protection standards that were established decades ago when more-limited data were available and nuclear-energy expansion was not a national priority. The review focuses on scientific evidence regarding the health effects of ionizing radiation at annual doses of 10,000 mrem or less. The review evaluates epidemiological studies, radiobiological research, and positions of relevant professional organizations to assess the balance of evidence regarding health effects at these dose levels. The preponderance of available evidence suggests that current radiation protection frameworks may be overly conservative. Epidemiological studies have consistently failed to demonstrate statistically significant adverse health effects at doses below 10,000 mrem delivered at low dose rates. Studies of populations with elevated natural background radiation have not shown conclusive evidence of increased cancer rates or other adverse health outcomes. Multiple major professional organizations acknowledge significant limitations and uncertainties in the linear no-threshold (LNT) model at low doses. Based on this assessment, we propose maintaining an annual occupational whole-body dose limit of 5,000 mrem/yr and eliminating all "as low as reasonably achievable" requirements and limits below this threshold. This change could potentially reduce radiation protection costs by millions and correct misconceptions about the risks associated with nuclear technologies. The evidence further supports future consideration of a 10,000 mrem/yr limit that may maintain sufficient safety margins while further reducing protection costs. Similarly, given the data and that the average annual radiation dose per person in the U.S. is 620 mrem, we believe the public dose limits of 100 mrem/yr are unnecessarily restrictive; increasing to 500 mrem/yr would maintain substantial safety margins while reducing regulatory burdens and associated bureaucracy. While we acknowledge ongoing scientific debate and encourage continued research on the health effects of ionizing radiation, our review indicates current frameworks are overly conservative. These overly stringent limits not only impose unnecessary economic burdens without corresponding health benefits but also divert safety focus and resources from more-important considerations. Although this study was motivated by nuclear-power considerations, reforms to radiation protection requirements have significant positive implications for other areas, such as nuclear medical applications, environmental remediation, nuclear-waste management and disposal, human space travel, and industrial applications of nuclear technologies.

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ACRONYMS

ACL	Administrative Control Level
AEC	Atomic Energy Commission
ALARA	As low as reasonably achievable
CFR	Code of Federal Regulations
CT	Computed tomography
DDREF	Dose and Dose-rate Effectiveness Factor
DOE	U.S. Department of Energy
DREF	Dose-rate effectiveness factor
EPA	Environmental Protection Agency
ERR	Excess relative risk
GAO	Government Accountability Office
HPS	Health Physics Society
ICRP	International Commission on Radiological Protection
INL	Idaho National Laboratory
LET	Linear energy transfer
LNT	Linear No-Threshold
LSS	Life Span Study
MCL	Maximum Contaminant Levels
MFC	Materials and Fuels Complex
MPS	Million Person Study
NCRP	National Council on Radiation Protection and Measurements
NRC	Nuclear Regulatory Commission
NRRW	National Registry for Radiation Workers
R&D	Research and development
TEDE	Total effective dose equivalent
UNSCEAR	United Nations Scientific Committee on the Effects of Nuclear Radiation

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EXECUTIVE SUMMARY

Recent executive orders[a] to "Usher in a Nuclear Renaissance," coupled with the U.S. Department of Energy's commitment to "Unleash Commercial Nuclear Power,"[b] the Nuclear Regulatory Commission's (NRC's) updated mission statement,[c] and the global commitment to triple nuclear energy capacity by 2050[d] have placed renewed emphasis on nuclear energy's importance for national security and economic prosperity. This heightened nuclear prioritization necessitates a critical assessment of factors impeding nuclear-energy deployment, including potentially overly conservative radiation protection requirements that have been debated for decades and may add unnecessary costs without commensurate health and safety benefits. Related, recent executive order entitled "Ordering the Reform of the Nuclear Regulatory Commission"[e] directs the NRC to "Adopt science-based radiation limits. In particular, the NRC shall reconsider reliance on the linear no-threshold (LNT) model for radiation exposure and the 'as low as reasonably achievable' standard, which is predicated on LNT."

Against this backdrop, this technical review examines current radiation protection standards established more than three decades ago when scientific data were more limited and nuclear-energy expansion was not a national priority. While acknowledging that the science on low-dose radiation effects remains unsettled with competing theories and ongoing debate, it evaluates contemporary scientific evidence regarding ionizing radiation's health effects at annual doses of 10,000 mrem or less, focusing on whether existing regulatory frameworks and associated implementation align with current scientific understanding while maintaining appropriate safety margins for both workers and the public.

KEY FINDINGS

Scientific Assessment

1 **Epidemiological Evidence**: Studies have generally not demonstrated statistically significant adverse health effects at doses below 10,000 mrem delivered at low dose rates, despite decades of research. Studies from areas with high natural background radiation (including regions in Kerala, India, and Ramsar, Iran) have not shown conclusive evidence of increased cancer rates or other adverse health outcomes, even with background radiation levels significantly exceeding regulatory limits.

2 **Radiobiological Evidence**: Cellular-repair mechanisms—including enhanced DNA-repair processes, adaptive responses, and potential hormesis effects—may reduce or eliminate harmful effects of radiation at low dose rates. These biological responses suggest that simple linear extrapolation of risks from high acute doses to low chronic doses may substantially overestimate actual biological effects.

3 **LNT-Model Limitations**: Major professional organizations increasingly acknowledge the limitations of the LNT model at low doses. The Health Physics Society explicitly states[f] that "below levels of about 100 mSv [i.e., 10,000 mrem] above background from all sources combined, the observed radiation effects in people are not statistically different from zero."

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[a] President Trump Signs Executive Orders to Usher in a Nuclear Renaissance, Restore Gold Standard Science, May 23, 2025.

[b] Memorandum from C. Wright, Secretary of Energy, to Heads of Departmental Elements, Unleashing the Golden Era of American Energy Dominance, February 5, 2025

[c] NRC Approves Updated Mission Statement, January 24, 2025.

[d] Six More Countries Endorse the Declaration to Triple Nuclear Energy by 2050 at COP29, November 2024.

[e] Ordering the Reform of the Nuclear Regulatory Commission, Executive Order 14300, May 23, 2025.

[f] Radiation Risk in Perspective, Position Statement PS010-4 of the Health Physics Society.

4 **Regulatory Evolution**: What began as a cautious policy based on the LNT model has evolved into an increasingly restrictive regulatory regime. The practical interpretation of "as low as reasonably achievable" (ALARA) has shifted from "reasonably achievable" to "as low as possible," driving implementation of administrative control limits and associated practices that go well beyond the original intent.

Economic and Practical Implications

1 **Implementation Reality**: Despite regulatory limits of 5,000 mrem/year, due to current ALARA requirements, actual exposures have been driven substantially lower. In 2023, only 22% of monitored DOE personnel received any measurable dose; of those, the average was just 50 mrem, 1% of the regulatory limit.[g] Over the past 5 years, only one monitored individual within DOE received a dose above the 2,000 mrem administrative control level. In Calendar Year 2022 (the latest available data from the NRC)[h], 58% of monitored individuals at commercial light-water reactors did not receive any measurable dose, and none received a dose greater than 3,000 mrem.

2 **Operational Impact**: Current requirements significantly affect nuclear power and facility economics through specialized personnel needs, extensive monitoring equipment, protective infrastructure, and administrative compliance costs. Similarly, current requirements have significant cost and schedule implications for decommissioning commercial nuclear power plants, nuclear-waste disposal, and nuclear-site cleanup, as well as medical and industrial applications of nuclear technologies.

3 **Public Perception Gap**: Research has established a significant disparity between public perception of radiation risks and scientific risk assessments. This perception gap influences social acceptance of nuclear technologies and demonstrates the need for more-effective risk communication alongside appropriate safety standards. Overly restrictive dose limits contribute to the misperceptions of radiation risk.

RECOMMENDATIONS

While recognizing ongoing scientific uncertainty, based on the balance of available scientific evidence and economic considerations, this report recommends:

1 **Occupational Dose Limits**: Maintain the annual occupational whole-body dose limit of 5,000 mrem and eliminate all ALARA requirements and limits below this threshold. This approach would maintain significant safety margins while reducing unnecessary economic burdens. In the future, consider the merits of increasing the occupational dose limit to 10,000 mrem/year with appropriate constraints. Note that other dose limits, including organ and tissue dose limits, should also be reevaluated, but are beyond the scope of this report.

2 **Public Dose Limits**: Revise the current public dose limit from 100 mrem per year to 500 mrem per year. This moderate increase would still maintain a significant safety factor relative to levels where effects might begin to be detectable, remain within the range of natural background variations observed globally, and better align with the average U.S. radiation exposure of 620 mrem annually.

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[g] U.S. Department of Energy, Office of Environment, Health, Safety & Security. 2024. "Occupational Radiation exposure Report for CY 2023."

[h] Occupational Radiation Exposure at Commercial Nuclear Power Reactors and Other Facilities 2022, NUREG-0713, Volume 44, October 2024.

3 **Regulatory Framework**: Modify the Environmental Protection Agency's (EPA's) complex multilayered approach with various pathway-specific and source-specific limits to create a more-coherent and scientifically justified regulatory framework based on the revised public dose limit of 500 mrem/year. Further, harmonize longstanding differences in radiation limits between relevant U.S. federal agencies.[i] An appendix provides a proposed implementation framework for regulatory reform.

4 **Risk Communication**: Develop improved strategies that more-accurately convey scientific evidence regarding low-dose radiation risks to both workers and the public, addressing the disproportionate fear that negatively impacts adoption of beneficial nuclear technologies and drives overly conservative regulatory approaches.

5 **Continued Research**: Support ongoing research on low-dose radiation effects to further refine scientific understanding and regulatory approaches. In the past five years, Congress has appropriated more than $50 million for low-dose research, including $20 million in Fiscal Year 2024 to restart the low-dose radiation research program administered by the Office of Science within the DOE. This research will further refine scientific understanding of low-dose radiation effects and inform regulatory approaches. Given the broad implications, consideration should be given to this research being coordinated through the White House Office of Science and Technology Policy.

CONCLUSION

While the science on low-dose radiation effects remains unsettled, the balance of available evidence suggests that current radiation protection standards warrant reconsideration. The recommendations outlined in this review have the potential to transform the economic landscape for nuclear applications while maintaining appropriate health and safety protections. By reducing unnecessary regulatory burdens, these revisions could dramatically improve the cost-competitiveness of nuclear energy, expand access to nuclear-medicine procedures, enhance industrial applications of nuclear technologies, benefit environmental remediation of former nuclear sites, and improve management and disposal of commercial nuclear wastes.

Consistent with guidance in Executive Order "Restoring Gold Standard Science,"[j] these changes could also begin to align public perceptions of radiation risk with actual scientific data. These benefits would arrive at a critical moment when nuclear technologies offer essential solutions to pressing societal needs: mitigating energy scarcity through reliable baseload capacity, enhancing energy security through diversified domestic sources, addressing energy poverty through access to affordable power, expanding access to lifesaving medical treatments and diagnostics, and driving industrial innovation across manufacturing, resource extraction, and specialized applications. Rather than claiming scientific certainty where none exists, these recommendations represent a balanced assessment that aligning radiation protection standards with current scientific understanding represents a prudent step toward realizing these benefits while maintaining appropriate safety margins for workers and the public.

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[i] Radiation Standards: Scientific Basis Inconclusive, and EPA and NRC Disagreement Continues, GAO/RCED-00-152, June 2000.

[j] Restoring Gold Standard Science, Executive Order 14303, May 23, 2025. "Highly unlikely and overly precautionary assumptions and scenarios should only be relied upon in agency decision-making where required by law or otherwise pertinent to the agency's action.", from Sec. 4. "Improving the Use, Interpretation, and Communication of Scientific Data."

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Reevaluation of Radiation Protection Standards for Workers and the Public Based on Current Scientific Evidence

1. INTRODUCTION

The United States faces unprecedented electricity-demand growth driven by artificial intelligence and data centers, industrial expansion, and widespread electrification. In response to this and other related factors, President Trump declared a National Energy Emergency[1] and recently issued executive orders[2] to "Usher in a Nuclear Renaissance." The administration's strategy explicitly prioritizes unleashing commercial nuclear power and streamlining regulatory burdens[3] while the Nuclear Regulatory Commission (NRC) has recently updated its mission statement[4] to emphasize enabling nuclear-energy deployment "for the benefit of society and the environment." Further, the United States[k] and more than 30 nations have made a landmark commitment to triple nuclear-energy capacity by 2050.[5] These coordinated actions underscore nuclear energy's critical importance to national security and economic prosperity while highlighting the urgency of nuclear expansion.

Against this backdrop of renewed nuclear prioritization, a critical assessment of factors impeding nuclear-energy deployment becomes essential. One issue that has been identified as needlessly adding to the cost of nuclear energy is excessively conservative requirements, particularly those related to radiation protection (examples include: 6,7,8,9,10). Most recently, Executive Order 14300, "Ordering the Reform of the Nuclear Regulatory Commission,"[11] directs the NRC to "Adopt science-based radiation limits. In particular, the NRC shall reconsider reliance on the linear no-threshold (LNT) model for radiation exposure and the 'as low as reasonably achievable' standard, which is predicated on LNT." Also applicable is Executive Order 14303, "Restoring Gold Standard Science,"[12] which directs that "Highly unlikely and overly precautionary assumptions and scenarios should only be relied upon in agency decision-making where required by law or otherwise pertinent to the agency's action."

Given these circumstances, this technical review examines radiation protection standards through the lens of contemporary scientific evidence regarding ionizing radiation health effects and their relationship to the economic and operational challenges facing nuclear energy expansion.

The science on low-dose radiation effects remains unsettled, with ongoing debate among experts and competing theoretical frameworks. For decades, radiation protection standards have been built upon the LNT model,[13,14] which assumes that radiation risk is directly proportional to dose, with no threshold below which the risk is zero. However, alternative theories, including threshold models and hormesis (potential beneficial effects at low doses), have gained scientific support. This scientific uncertainty has been the source of much debate[15,16] and has driven the implementation of the "as low as reasonably achievable" (ALARA) principle—requiring exposures to be kept ALARA regardless of dose level.

[k] Note that Executive Order "Ordering the Reform of the Nuclear Regulatory Commission" states "It is the policy of the United States to: …Facilitate the expansion of American nuclear energy capacity from approximately100 GW in 2024 to 400 GW by 2050."

When regulatory bodies established this framework in the mid-20th century, scientific data on low-dose radiation effects was limited. Their conservative approach, extrapolating risks observed at high, acute doses to much-lower chronic doses, reflected a precautionary stance given the knowledge limitations of that era. However, what began as a cautionary, conservative policy has evolved over time into an increasingly restrictive regulatory regime. The practical and subjective interpretation of ALARA has shifted from "reasonably achievable" to "as low as possible"—driving the implementation of administrative control limits and similar requirements that go well beyond the original intent of the principle. [m] The continual lowering of ALARA-based dose limits led to the abandonment of ALARA's original principle: carefully balancing the benefits of dose reduction against the costs of implementation.

While scientific consensus on low-dose effects remains elusive, the accumulated evidence over recent decades suggests that current regulatory approaches may be overly conservative. Extensive epidemiological studies, radiobiological research, and analyses of populations with chronic elevated exposures have generated considerable data on radiation effects at low doses. Research focusing on areas with high natural background radiation,[17,18,19] nuclear industry workers,[20,21,22] and medically exposed cohorts,[23,24,25] has significantly expanded our understanding of radiation's health effects. This growing body of evidence, while not definitive, suggests that doses below certain thresholds may not produce statistically significant negative health effects,[26,27,28] challenging some fundamental assumptions underlying current radiation protection frameworks.

We recognize that scientific uncertainty does not automatically justify regulatory change. However, the economic and operational consequences of the current regulatory approach are widely understood to be significant. The ALARA-based framework imposes additional engineering, design, operational, administrative, and training requirements that contribute to significant costs across nuclear applications, including increased expenses for nuclear-energy generation and nuclear-waste management, reduced availability of beneficial medical procedures,[29,30,31] and barriers to industrial applications of radiation.[32,33] These impediments limit society's ability to fully realize the benefits of nuclear technologies in addressing critical challenges in energy security, national security, medical-treatment access, and industrial innovation.

This review critically examines the scientific evidence regarding health effects from radiation dose levels relevant to occupational and public whole-body exposure limits. Rather than claiming scientific certainty where none exists, we assess whether the balance of available evidence supports the current level of regulatory conservatism. Our goal is to determine whether regulatory frameworks should be revised to better align with the weight of contemporary scientific understanding while maintaining appropriate safety margins for both workers and the public, acknowledging that some level of scientific uncertainty will likely persist and that the full societal benefits of expanding nuclear power are difficult to quantify.

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[m] Numerous influential organizations, including the NRC, the Institute for Nuclear Power Operations (INPO), and state regulators, have emphasized lower ALARA-based dose limits through tracked metrics and related mechanisms to indicate radiological program health. The focus on these indicators has led to a marked shift over time from the original ALARA concept.

2. BACKGROUND

2.1. Radiation Dose and Health Effects

2.1.1. Dose Quantities and Units

Radiation dose can be quantified using several different metrics:[34,35,36]

- Absorbed dose (measured in gray [Gy] or rad): the energy deposited per unit mass of tissue
- Equivalent dose (measured in sievert [Sv] or rem): the absorbed dose weighted by radiation type
- Effective dose (measured in sievert [Sv] or rem): the equivalent dose weighted by tissue sensitivity.

For the purposes of this review:

- Dose will be discussed in terms of mrems, with conversion from other units applied where necessary (1 mSv = 100 mrem; 1 rad ≈ 1,000 mrem for gamma/beta radiation), and
- Low dose (and the low dose region) is defined as less than 10,000 mrem of low-linear energy transfer (LET) radiation to organs and tissues and low dose rates less than 500 mrem/hr.

2.1.2. Acute vs. Chronic Exposure

Radiation exposure manifests in two fundamentally different temporal patterns, acute and chronic, each producing distinct biological responses in exposed organisms.[37,38] Acute exposure occurs when radiation is delivered over a short timeframe, often in a single high-dose event, while chronic exposure involves continuous or intermittent low-dose radiation over extended periods, typically months to years or even lifetimes.

Acute high-dose radiation produces deterministic effects, also known as tissue reactions, which emerge only when exposure exceeds specific threshold values. These effects include radiation sickness (acute radiation syndrome), nausea, diarrhea, reddening of the skin (erythema), and damage to specific organs and tissues. Cataracts[39] are a good example of a deterministic effect in the nuclear medicine field. Strong beta-emitting isotopes such as yttrium are used to constrict blood vessels; this presents a hazard to oncologists along with the need for appropriate eye protection. Unlike stochastic effects, which are based on theoretical probability, risk-assessment models involving very low chronic exposures, deterministic effects demonstrate increasing severity with higher doses. The affected tissues show progressive deterioration as more cells are damaged or killed by intense radiation. These effects generally manifest at varying doses and dose rates depending on the organ or tissue and the endpoint under consideration. Such high-dose, acute exposures are rare outside of radiotherapy treatments, nuclear accidents, or nuclear-weapons detonations, making them less relevant to typical occupational or public-exposure scenarios.

In contrast, chronic exposure at lower dose rates primarily raises concerns about potential stochastic effects—predominantly cancer. Recent studies have investigated correlations between chronic low-level radiation exposure and various health effects, including Parkinson's disease and cardiovascular effects.[40,41] However, it is important to stay focused on the central issue with LNT: that all radiation exposure, without threshold, will create deleterious health effects—an assumption widely interpreted as cancer risk. The example of Parkinson's disease illustrates this distinction. While Parkinson's involves cognitive decline that is certainly harmful, it is not cancer, nor has radiation been causally linked to the disease's onset. As with most medical conditions, numerous environmental and genetic factors typically contribute to disease development, making it difficult to establish the magnitude of each factor's contribution. Unlike deterministic effects, stochastic effects are probabilistic in nature; under the LNT model, their likelihood rather than severity is assumed to increase proportionally with dose, without any threshold below which the risk disappears entirely.[6,42,43]This fundamental assumption underpins current radiation protection frameworks worldwide. The scientific evidence supporting or challenging this assumption for chronic exposures below 10,000 mrem/year constitutes the central focus of this review.

Understanding whether chronic low-dose exposures truly follow linear risk patterns has profound implications for radiation protection standards, nuclear-energy deployment costs, and the balance between radiation safety and beneficial nuclear applications. As Brooks concludes, "very large amounts of radiation are required to produce cancer."[44]

2.1.3. Linear No-Threshold Theory

The LNT theory currently underpins radiation protection regulation. LNT was born from the work of early scientists (geneticists) who investigated the conditions that cause gene mutation. Early (mid-1920s) work by Gilber Lewis, Axel Olson, Hermann Muller, and Thomas Hunt Morgan investigated the genome under the hypothesis that natural and cosmic background radiation were mechanisms for evolution, thereby forming the premise of no-threshold dose response. Muller used doses to drosophila flies at 100,000,000 times greater than the natural and cosmic background radiation delivered over very short time periods. This work predates our current understanding of the genome and gene repair. Muller theorized that cumulative dose (no threshold) was the best predictor of gene mutation, not accounting for repair, and did linear extrapolation from the high-dose (and high-dose-rate) populations, as seen in the following quote from Muller's Nobel Prize speech of December 12, 1946: "In our most recent work with Ray-Chaudhuri... these principles [the LNT single-hit theory] have been extended to total dose as low as 400 *r*, and rates as low as 0.01 *r* per minute, with gamma rays. They leave, we believe, no escape from the conclusion that there is no threshold dose . . ."[45,46]

This report recognizes that competing scientific opinions exist regarding actual health effects from low-dose radiation exposure. The objective is to promote practical improvements to implementation by restoring the balanced approach previously employed in radiation protection. While both LNT and hormesis remain theoretical frameworks, current regulatory limits have been primarily based on LNT theory. When the ALARA concept was first introduced, cost-benefit analyses appropriately balanced dose reduction against economic impact. However, as dose limit recommendations were continually lowered over time, this balanced consideration of dose savings versus financial costs diminished. This paper advocates returning to that balanced approach, informed by the current body of scientific evidence.

2.1.4. Typical Radiation Dose to Members of the General Public in the United States

Americans and people around the world are continuously exposed to radiation from both natural and man-made sources.[47] According to the most current official figure from the National Council on Radiation Protection and Measurements (NCRP), Report No. 160,[48] the average American receives approximately 620 mrem annually. This number represents a marked increase from the 360 mrem average[49] established in the 1980s, a change driven primarily by the expanding use of medical imaging in modern healthcare. When considering this number, it should be noted that there is considerable variability among individuals, primarily depending on medical exposure, and this is an evolving estimate based on assessments of medical exposures.[n,50]

Natural background radiation contributes approximately half of this total exposure. This includes radon and thoron gases that seep into our homes from soil, cosmic radiation from space (which increases with elevation), terrestrial radiation from soil and rocks, and internal radiation from naturally occurring radioactive materials in food and water. The ubiquity of these natural sources means that radiation exposure is an unavoidable aspect of life on Earth, though levels vary geographically based on factors like soil composition, elevation, and local geology.

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[n] NCRP Report No. 184 (published in 2019) updated the medical exposure component, evaluating doses for the 2016 timeframe, but this was specifically focused on medical radiation exposure rather than updating the total population dose estimate. Report No. 184 found that medical radiation doses had decreased by approximately 60-80 mrem (depending on methodology applied) between 2006 and 2016. It is anticipated that, in the future, NCRP will officially update the 620 mrem figure downward to reflect this more recent work.

The other half of our radiation exposure comes predominantly from medical procedures. Computed tomography (CT) scans, positron-emission tomography scans, and nuclear-medicine procedures alone account for roughly 36% of Americans' total radiation exposure and 75% of all medical radiation exposure.[51] The dramatic growth in these diagnostic tools explains most of the increase in average radiation exposure over recent decades. Conversely, these advances in technological medical imaging have helped identify cancer earlier, resulting in improved health outcomes. A smaller fraction comes from conventional X-rays, consumer products, industrial applications, and occupational exposures.

Individual exposure varies considerably based on personal circumstance. Someone living at high elevation in a home with elevated radon levels who undergoes multiple CT scans might receive significantly more than the average 620 mrem while a person at sea level with minimal medical imaging might receive substantially less. These variations make radiation exposure highly individualized, despite the published averages.

For context, the current average exposure of 620-mrem remains well below levels associated with observable health effects. The occupational limit for radiation workers stands at 5,000 mrem annually,[52,53] and the Health Physics Society (HPS) indicates that health effects below 10,000 mrem are either too small to observe or nonexistent.[54] Some inhabited regions globally experience natural background radiation exceeding 1,000 mrem annually without demonstrable adverse health consequences.[55] This context is important when considering the appropriate balance between radiation protection standards and their practical implementation in various fields.

For public doses, it is important to consider public perception and fear related to radiation exposure. This perception has been influenced by popular culture and the nuclear industry's message that *any dose, no matter how small, carries a slight risk of cancer.* This disclaimer has reinforced this perception without regard to the benefits of reliable power and has not served the industry's efforts to reasonably manage doses within the low-dose region. As a result, people are unnecessarily put at risk from grid unreliability, reduced access to medical procedures, and lost economic-development opportunities. As one major energy industry report[56] notes, "Making energy more expensive or unreliable compromises people, national security, and the environment." This principle applies directly to radiation protection policies, where addressing these issues can have enormous positive impacts on improving the quality and quantity of life in the U.S. and around the world.

International Comparison

The average American's annual radiation dose of 620 mrem is notably higher than the worldwide average of approximately 240 mrem from natural background radiation. This difference is largely attributable to the United States' higher utilization of medical-imaging procedures rather than differences in natural background radiation. When considering only natural sources, the worldwide average is approximately 240 mrem while the U.S. natural background averages about 310 mrem.[57]

Natural background radiation varies significantly around the world. Canada reports a lower average natural dose of approximately 180 mrem per year while residents in certain regions receive substantially higher doses: Kerala Coast in India averages about 1,250 mrem annually, and Yangjiang, China, experiences approximately 630 mrem per year. Even more extreme are the high background natural radiation areas in parts of Iran where geological characteristics result in doses that can reach more than 26,000 mrem annually.[58]

These international variations stem from differences in local geology (concentrations of naturally radioactive elements in soil and rock), altitude (affecting cosmic radiation), radon levels, and lifestyle factors. Medical exposure further complicates the comparison, with developed nations generally having higher medical contributions to total dose. Despite these differences, epidemiological studies in areas of high background radiation have generally not demonstrated conclusive evidence of increased cancer rates or other adverse health effects that are attributable to chronic low-level radiation exposure.[59]

Citing high background studies is not meant to be dispositive; rather, it is meant to illustrate that there are examples of non-occupational doses that seem to contradict the theory that all responses can result in negative health effects.

2.1.5. A Brief History of Radiation Protection Regulations and Practices

The evolution of radiation protection standards reflects a century-long journey from initial discovery to increasingly formalized regulation. Following the discoveries of X-rays by Wilhelm Röntgen in 1895 and radioactivity by Henri Becquerel in 1896, early applications in medicine and industry proceeded with little recognition of potential hazards. By 1911, however, over 90 cases of radiation-induced skin cancers had been reported among early radiation workers.[60] During this early period, no standardized methods existed for measuring exposure or calculating doses, leaving radiation workers with little guidance for self-protection.[61]

The 1920s marked a turning point, when Harrison Martland's investigations in 1925 linked radium ingestion by watch-dial painters to serious illness and death.[62] This compelling evidence of radiation's harmful effects catalyzed the international community to establish the first coordinated radiation protection efforts. In 1928, the International Commission on X-Ray and Radium Protection (later renamed the International Commission on Radiological Protection [ICRP]) was formed,[63] and in 1929, the National Council on Radiation Protection and Measurements was formed and later reorganized and chartered by the U.S. Congress in 1964 as the NCRP. By 1934, both national and international radiation protection communities had established the concept of a "tolerance dose" of approximately 200 mrem per day—a level believed to cause no observable harmful effects.[64]

The nuclear age dramatically transformed radiation protection following the atomic bombings in 1945. Nuclear fission and fusion technologies introduced new radionuclides and exposure scenarios while the development of nuclear power, expansion of medical applications, and Cold War nuclear testing created unprecedented challenges.[65] In response, protection authorities transitioned from the "tolerance dose" concept to a "maximum permissible dose" approach, recognizing that any radiation exposure might carry some risk. The NCRP introduced a maximum permissible dose of 300 mrem per week for whole-body exposure in 1954.[66] By 1957, the U.S. Atomic Energy Commission (AEC) had incorporated radiation protection standards into federal regulations through 10 Code of Federal Regulations (CFR) Part 20, formally codifying radiation protection into law.[67]

"In 1957, the ICRP recommended an annual occupational dose limit of 5 rem per year, and in 1958 the NCRP recommended a life-time occupational dose limit of [(age in years – 18) × 5] rem, or a limit of 235 rem for someone who works from ages 18 to 65. The NCRP also recommended an annual limit to the public of 500 mrem per year. In 1960, the Federal Radiation Council recommended an annual limit of 500 mrem per year for an individual in the general public and a limit of 170 mrem per year as the average annual dose to a population group."[68]

The 1960s and early 1970s witnessed another significant shift as mounting concerns about genetic effects and cancer led radiation protection authorities to embrace the LNT model. This model, which assumes that any radiation dose carries some risk and that this risk is directly proportional to dose, without a threshold, was adopted primarily as a conservative approach in the face of scientific uncertainty, as formalized in the 1972 Biological Effects of Ionizing Radiation (BEIR) I report.[69] Simultaneously, the concept of "as low as practicable" (later termed "as low as reasonably achievable") became a cornerstone of radiation protection philosophy when the AEC formally introduced it in 1971,[70] requiring exposures to be reduced below regulatory limits when reasonably achievable.

Modern radiation protection crystallized in 1977 when the ICRP established three fundamental principles that continue to guide practice today: justification (requiring net benefit), optimization (implementing ALARA), and limitation (setting maximum individual doses).[71] These principles represented a significant philosophical shift from earlier approaches, moving from purely threshold-based protection to a risk-informed system. In 1987, ALARA was formalized in the Federal Register,[72] which included the following recommendation:

> *No exposure is acceptable without regard to the reason for permitting it, and it should be general practice to maintain doses from radiation to levels below the limiting values specified in these recommendations. Therefore, it is fundamental to radiation protection that a sustained effort be made to ensure that collective doses, as well as annual, committed, and cumulative lifetime individual doses, are maintained as low as reasonably achievable (ALARA), economic and social factors being taken into account.*

Also in 1987, the NCRP issued updated recommendations in Report No. 91, which included reducing the annual occupational dose limit to 5 rem.[73] The NRC revised 10 CFR Part 20 in 1991 to align with these updated recommendations, implementing the current U.S. regulatory framework that emphasizes ALARA as a regulatory requirement rather than just a goal.[74] It is interesting to note that nearly all of the commercial nuclear power plants operating in the U.S. were licensed prior to 1991.

Throughout this evolution, radiation protection standards have become increasingly conservative, with annual occupational-dose limits decreasing from approximately 25,000 mrem/year (based on early tolerance doses) to today's limit of 5,000 mrem/year—a 5-fold reduction[75]—and the Department of Energy's (DOE's) administrative control level (ACL) or 2,000 mrem/year (see Figure 1). This reduction reflects both the advancing scientific knowledge of the time and a precautionary, conservative approach to managing radiation risks. However, as this report concludes, the accumulation of scientific evidence over recent decades raises questions about whether current standards, which remain largely unchanged since their introduction in the early 90s, remain appropriately balanced between protection and practical implementation.

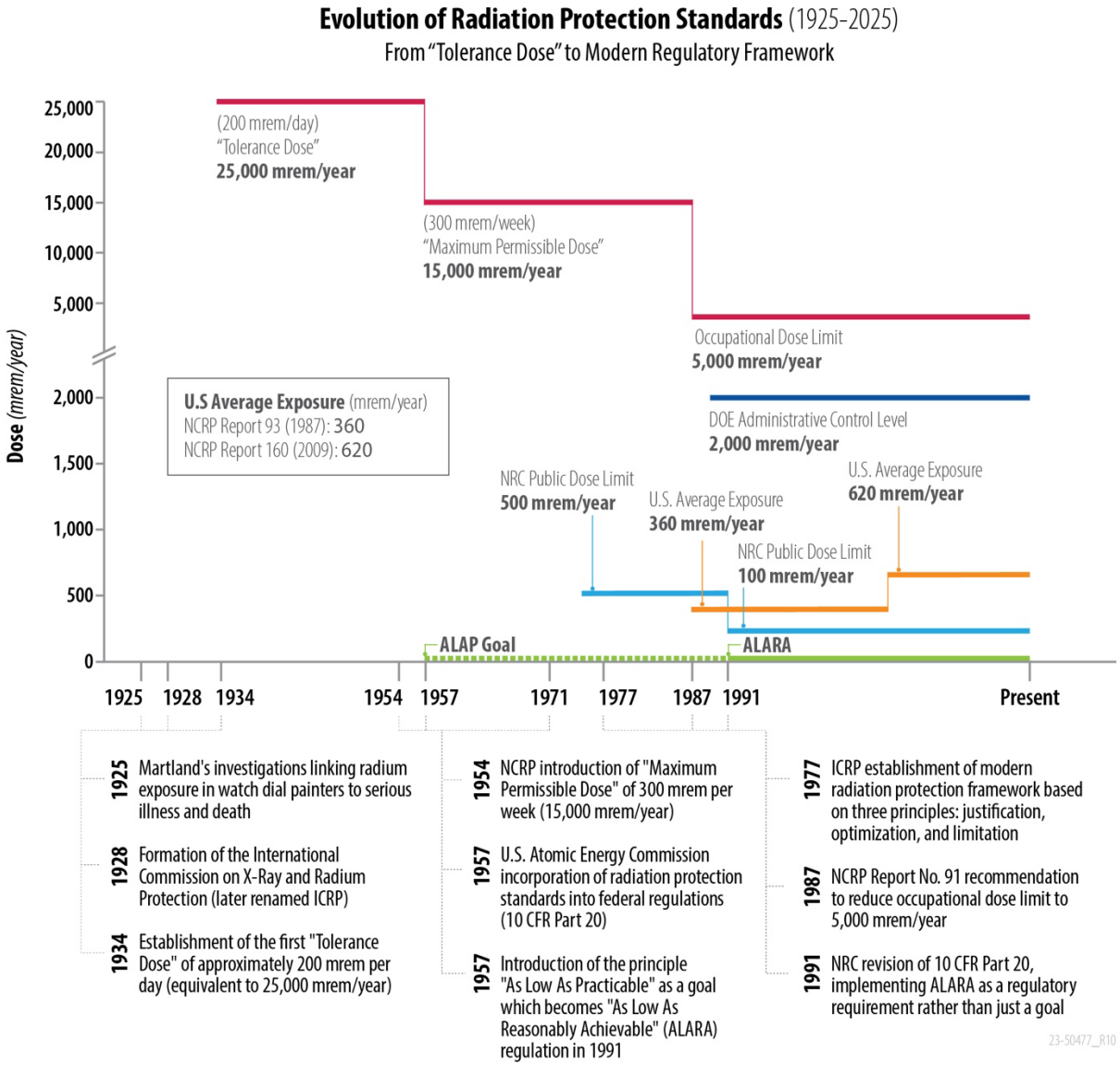

Figure 1. Evolution of radiation protection standards. (Note: Due to the complexity of the Environmental Protection Agency's (EPA's) regulations for specific radiation sources and that they often exceed the stringency of NRC and DOE requirements, the evolution of the EPA standards is not included in this figure. See Section 2.2.2 and EPA's "Radiation Regulations and Laws"[76] for more information on EPA radiation standards.)

2.2. Current Regulatory Standards

2.2.1. International Commission on Radiological Protection

The ICRP developed a comprehensive framework of dose limits that has profoundly shaped radiation protection regulations worldwide. For occupational exposures, the ICRP recommends a nuanced approach that attempts to balance practical operational needs with radiation-safety considerations. Their current guidance establishes an occupational dose limit of 2,000 mrem per year, calculated as an average over a 5-year period, with the additional constraint that no single year should exceed 5,000 mrem. This averaging approach allows for some operational variability while maintaining overall exposure control. These recommendations serve as the fundamental basis for radiation protection frameworks in most nations and international organizations.[35]

The evolution of the ICRP's framework for dose limits has profoundly shaped radiation protection regulations worldwide as a *de facto* consensus standard. In the 1990s, 10 CFR 20 was revised to adopt ICRP Publication 26 guidance while 10 CFR 835 was revised again in 2007 using the guidance in ICRP Publication 60 to establish its regulatory limits. With respect to occupational exposures, the ICRP has continued to recommend further reductions to these limits. Most recently ICRP Publication 147, "Use of Dose Quantities in Radiological Protection," recommends establishing an occupational dose limit of 2,000 mrem per year, calculated as an average over a 5-year period, with the additional constraint that no single year should exceed 5,000 mrem. Ostensibly, this averaging approach was to allow for some operational variability while maintaining overall exposure control. These recommendations serve as the fundamental basis for radiation protection frameworks in most nations and international organizations. However, while presented as a nuanced approach that attempts to balance practical operational needs with radiation-safety considerations, the underlying philosophy of these new recommended lower limits are primarily based on the fact that facilities can operationally achieve these lower recommendations rather than on some type of observable effect at 5,000 mrem/yr. This follows a distinct pattern by the ICRP to create recommendations without regard to costs or discernable health effects. In fact, in the same ICRP Publication 147 document, low dose is referred to as less than 100 mGy (10,000 mrad) of low-LET radiation to organs and tissues and low dose rates less than 5 mGy per hour (500 mrad/hr): this further demonstrates ICRP's drive to limit occupational exposures far below what could be deemed reasonable.[35,77,78]

For public exposures, the ICRP applies a substantially more-conservative standard, recommending a dose limit of 100 mrem per year—less than 1/6th the average individual exposure in the U.S. of 620 mrem per year. This value represents a significant reduction—approximately 1/20th to 1/50th of the occupational limit—reflecting two key considerations. First, the general public includes potentially more-radiosensitive populations, including children, pregnant women, and individuals with certain medical conditions who may face greater health risks from radiation exposure. Second, public exposure is generally involuntary and occurs without the informed consent, radiation-awareness training, or monitoring afforded to radiation workers. These factors have led radiation protection authorities to implement this more-restrictive approach to public exposures. The substantial difference between occupational- and public-dose limits demonstrates how policy judgments regarding the acceptability of risk differ between voluntary- and involuntary-exposure scenarios, even when working from the same underlying scientific evidence.

2.2.2. Current Regulatory Limits

Radiation protection standards within the U.S. and across major global jurisdictions vary and are inconsistent, reflecting a lack of coordination within U.S. federal agencies such as NRC, DOE, and EPA, to the adoption of more-restrictive recommendations within the international community. In the United States, while NRC and DOE both maintain an occupational dose limit of 5,000 mrem per year, the DOE adds an administrative control level of 2,000 mrem per year. This is only one of many specified dose

limits and constraints. While the NRC uses 10 CFR 20, based on the recommendations in ICRP-26/30, and DOE uses 10 CFR 835, based on the recommendations in ICRP-60/66, there are other limits, constraints, dose coefficients, etc., that vary between these two regulations that have created differences in approaches to radiological protection activities within the US. In some instances, the U.S. EPA generally defers to the NRC and DOE for occupational limits when focusing primarily on public exposures; however, the EPA uses multiple pathway-exposure models; consequently, they have more-restrictive limits for air emissions and drinking water. In contrast, the European Union has adopted the ICRP-103 recommendation of 2,000 mrem averaged over 5 years, with no single year exceeding 5,000 mrem while Japan and Canada both permit 5,000 mrem annually while adding a cumulative limit of 10,000 mrem over any 5-year period, creating an effective long-term average similar to the European approach. While there are differences in implementation approach and limits, especially in the international community, it is recommended that an effort be made across federal agencies to use consistent and complementary standards for U.S.-based organizations. Further, the U.S. is the leader in nuclear-energy development and usage. When U.S. reactor developers propose new designs, they typically follow NRC-developed design criteria; however, this will also include consideration for international markets and these differences are factored in. Knowing this, U.S. regulatory policy should only consider the domestic market because international rules have such a high degree of variability.

While occupational dose limits have different approaches and variations, public-dose limits show greater consistency, with most major jurisdictions setting them at 100 mrem per year—approximately 1/50th of the average maximum occupational limits. This consistent ratio reflects a global consensus on the appropriate balance between worker and public protections. The EPA presents the primary exception with its more-complex framework of medium-specific and facility-specific limits, often ranging from 10–25 mrem annually. Most regulatory authorities further require that emissions from specific nuclear facilities be restricted to only a fraction of the overall public limit. The NRC, for instance, mandates that nuclear power plant emissions produce no more than 3–5 mrem annually to the most-exposed member of the public. For perspective, these regulatory limits should be considered against the average annual radiation dose of 620 mrem per person in the U.S.

Current regulatory limits for radiation workers and members of the public are summarized in Table 1.

Table 1. Current regulatory limits by jurisdiction.

Jurisdiction	Annual Occupational Dose Limit	Annual Public Dose Limit
United States (NRC)	5,000 mrem	100 mrem
United States (DOE)	5,000 mrem, with Administrative Control Level of 2000 mrem	100 mrem
United States (EPA)	Defers to NRC and DOE for occupational limits	10–25 mrem (facility specific) Additional limits for drinking water (4 mrem) and air (10 mrem).
European Union	2,000 mrem, averaged over 5 years, no year > 5,000 mrem	100 mrem
Japan	5,000 mrem per year, 10,000 mrem over 5 years	100 mrem
Canada	5,000 mrem per year, 10,000 mrem over 5 years	100 mrem

U.S. Nuclear Regulatory Commission Framework

The NRC's radiation protection framework, codified in 10 CFR 20, establishes a comprehensive system centered on an occupational exposure limit of 5,000 mrem per year total effective dose equivalent (TEDE). This general limit is supplemented by tissue-specific protections: 15,000 mrem annually for the lens of the eye and 50,000 mrem for skin and extremities. The regulations provide additional safeguards for vulnerable populations, limiting declared pregnant workers to 500 mrem during the entire gestation period and restricting exposures to minors under 18 to just 500 mrem annually—10% of the standard adult limit.

The NRC's approach extends beyond simple numerical limits to include detailed operational requirements for radiation surveys and monitoring (10 CFR 20.1501), personnel dosimetry (10 CFR 20.1502), hazard communication through posting and access control for radiation areas (10 CFR 20.1601–1602), and comprehensive recordkeeping (10 CFR 20.2101–2110). Together, these elements create a multifaceted system designed to provide defense-in-depth protection against radiation hazards.

Perhaps most significantly, the NRC has explicitly integrated the ALARA principle into its regulatory framework through 10 CFR 20.1101.[74,79] This regulation requires licensees to develop and implement radiation protection programs that employ procedures and engineering controls to achieve doses ALARA. Programs must be formally documented with written procedures and policies, reviewed at least annually, and must explicitly consider economic and social factors in ALARA implementation. Licensees must also establish investigation levels for occupational exposures that trigger reviews and investigations by radiation protection management when exceeded.

NRC Regulatory Guide 8.10, "Operating Philosophy for Maintaining Occupational Radiation Exposures ALARA," elaborates on these requirements, outlining essential elements of an acceptable ALARA program.[79] These include management commitment demonstrated through written policy statements, ongoing worker training in ALARA principles, radiation-safety committee oversight for complex operations, and clear authority for radiation-safety officers to enforce ALARA practices. Facilities must also modify designs and operations based on operating experience, establish tiered investigation levels for individual exposures, conduct job-specific ALARA reviews for high-exposure activities, and implement systems for tracking both individual and collective dose trends.

Further guidance in NRC Regulatory Guide 8.8 addresses facility-design considerations and operational practices.[80] These include recommendations for optimizing facility layout and equipment design, implementing remote-handling tools and robotics, designing effective ventilation systems, reducing source terms, establishing decontamination facilities, and deploying comprehensive radiation-monitoring systems. Collectively, this regulatory framework transforms ALARA from a philosophical aspiration into a binding legal requirement. Licensees must reduce doses below the 5,000 mrem limit regardless of economic impact because ALARA implementation is an explicit regulatory obligation rather than simply a goal or ideal. This comprehensive approach has proven to be overly effective at minimizing exposures well below the regulatory limit: in Calendar Year 2022 (the latest available data),[81] 58% of monitored individuals at commercial light-water reactors did not receive any measurable dose, and none received a dose greater than 3,000 mrem (60% of the regulatory limit). Further analysis of radiation exposure data from the NRC corresponding to commercial light-water reactor operations reveals that during the time period from 1973 and 2022 the "average measurable dose per individual" and the "average collective dose per megawatt-year" have decreased by more than a factor of 9 and 32, respectively (see Figure 2).

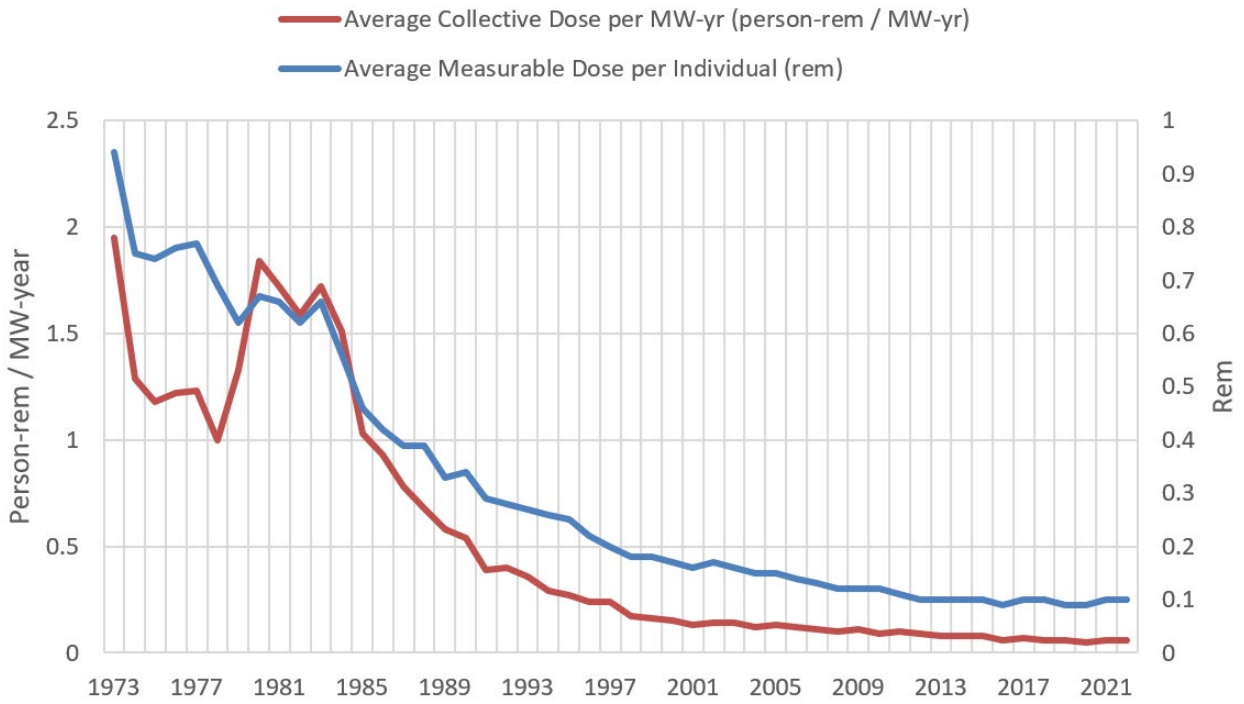

Figure 2. Evolution of occupational radiation exposure at U.S. commercial power reactors. Source: Occupational Radiation Exposure at Commercial Nuclear Power Reactors and Other Facilities (NUREG-0713).

U.S. Department of Energy Radiation Protection Framework

DOE developed a particularly sophisticated radiation protection system under 10 CFR 835, "Occupational Radiation Protection."[53] This comprehensive framework applies across all DOE activities and contractor operations involving radiation exposure, encompassing national laboratories, nuclear-weapons facilities, and environmental-cleanup sites. The DOE system stands out for its multitiered approach to exposure control.

At the highest level, DOE maintains the standard regulatory dose limit of 5,000 mrem per year, total effective dose, for radiation workers, establishing the maximum legally permissible exposure. However, the department applies a DOE-wide ACL of 2,000 mrem annually, effectively reducing the practical limit by 60%. Further, most DOE facilities implement even more-restrictive local ACLs, typically ranging from 500–1,500 mrem per year. In addition, formal ALARA programs establish numerical dose goals for specific operations generally set well below these facility-specific ACLs. This tiered structure creates multiple layers of protection well before approaching regulatory limits.

The DOE system includes specialized exposure categories similar to NRC regulations: 15,000 mrem annually for the lens of the eye; 50,000 mrem for extremities (hands, arms below the elbow, feet, and legs below the knees), organs, tissues, and skin; 500 mrem during gestation for declared pregnant workers; and 100 mrem for both members of the public in controlled areas and minors under 18 years old. However, DOE implements these limits through distinctively rigorous procedural controls.

All work in radiological areas requires radiological work permits that specify monitoring requirements and dose constraints. Exposures exceeding the 2,000 mrem DOE-wide ACL necessitate approval from the DOE Headquarters Program Secretarial Official or designee while any exposure above 1,000 mrem in a year triggers formal documentation and review requirements. In exceptional circumstances, regulations allow for planned special exposures, permitting a "radiological worker to receive doses in addition to and accounted for separately from the doses received under the limits specified in § 835.202(a)," though these require rigorous justification and approval and are rarely employed in practice.

The DOE framework includes comprehensive monitoring and recordkeeping provisions. Mandatory individual monitoring applies to anyone likely to receive more than 100 mrem annually. Detailed dose records must be preserved for the lifetime of the facility, plus 75 years, and comprehensive dose statistics are reported annually to DOE headquarters. Formal investigations are required for any exposure exceeding 80% of applicable limits or for unexpected exposure trends.

Training requirements further distinguish the DOE approach. Radiological Worker I certification is mandatory for unescorted access to radiological areas (exceeding 5 mrem/hr or with potential low levels of contamination) while Radiological Worker II certification is required for higher-hazard activities or areas with contamination or airborne radioactivity. Annual requalification ensures ongoing competence, and a programmatic standardized qualification, Radiation Protection Technician, ensures consistency among monitoring personnel.

Fundamentally, the DOE system enforces protection through a defense-in-depth philosophy that prioritizes engineered controls first, followed by procedural controls, before relying on individual worker practices or monitoring. Each facility must implement a formal radiation protection program, subject to DOE approval, continuous DOE oversight with an occurrence-reporting system, and periodic assessment. This stringent approach has proven effective at minimizing exposures well below the regulatory limits—in Calendar Year 2023, "only 22 percent of the monitored individuals received a measurable dose (a detectable dose greater than zero), and, of those, the average measurable dose received was 1 percent [50 mrem] of the 5 rem (50 mSv) TED limit."[82] Further, "Over the past 5 years, only one monitored individual . . . received a dose above the 2 rem (20 mSv) TED administrative control level," despite the 5,000 mrem regulatory limit. The DOE system exemplifies how a tiered approach of regulatory limits, administrative controls, and ALARA programming manage radiation exposure to be exceedingly lower than the formal limits.

U.S. Environmental Protection Agency Radiation Standards

The EPA established a complex, multilayered framework of radiation protection standards that often exceeds the stringency of NRC and DOE requirements, particularly for public exposures. This web of regulations creates a more-restrictive environment than would be suggested by the nominal 100 mrem/year public-dose limit used by other agencies.[83,84]

The EPA's Environmental Standards for the Uranium Fuel Cycle (40 CFR 190) limits radiation doses to the public from normal operations of nuclear-fuel-cycle facilities (excluding uranium mining and waste disposal) to 25 mrem/year to the whole body, 75 mrem/year to the thyroid, and 25 mrem/year to any other organ. The agency's National Emission Standards for Hazardous Air Pollutants under 40 CFR 61 further restrict airborne emissions of radionuclides to levels that would cause no member of the public to receive an effective dose equivalent exceeding 10 mrem/year—less than 1/60th of the average individual exposure in the U.S. of 620 mrem per year. Additionally, the Environmental Radiation Protection Standards for Nuclear Power Operations (40 CFR 190) specifically limit releases of long-lived radionuclides from the entire uranium fuel cycle.

The EPA's Drinking Water Standards (40 CFR 141) establish maximum contaminant levels for various radionuclides in public water supplies: combined radium-226/228 must not exceed 5 picocuries per liter (pCi/L); gross alpha particle activity is limited to 15 pCi/L; beta particle and photon radioactivity must not exceed levels producing 4 mrem/year; and uranium concentrations cannot exceed 30 micrograms per liter. These values are based on the National Bureau of Standards Handbook 69, published in 1963, and have not been revised with advances in biokinetic and dosimetric modeling. As a result, using these outdated dose factors causes some radionuclide concentrations to be more restricted than the originally intended 4 mrem/yr.

For remediation of contaminated sites under the Comprehensive Environmental Response, Compensation, and Liability Act (i.e., "Superfund"), the EPA generally applies a risk range of 10^{-4} to 10^{-6} excess lifetime cancer risk, which translates to cleanup levels equivalent to doses between 1 and 25 mrem/year. Similarly, the Environmental Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes (40 CFR 191) limit exposures to 15 mrem/year for the first 10,000 years after disposal. The Public Health and Environmental Radiation Protection Standards for Yucca Mountain, Nevada (40 CFR 197), established a 15 mrem/year limit for the first 10,000 years, increasing to 100 mrem/year for the period from 10,000 to 1 million years. In most of these standards, a combined risk from multiple radionuclides approach is employed. The net result is that individual nuclide risk targets can be set below levels that are measurable in environmental media by conventional radioanalytical methods.

This complex regulatory structure, with its media-specific and facility-specific standards, often ranging from 10–25 mrem/year, creates a significantly more-stringent regulatory environment than implied by the basic 100 mrem/year public-dose limit. The EPA standards typically fall 25–60 times lower than the average annual radiation dose of 620 mrem per person in the U.S., reflecting a highly conservative approach to radiation protection.

2.3. Positions Of Professional Organizations

Professional scientific and regulatory organizations have taken varying positions on radiation risk at low doses, reflecting both the evolving scientific understanding and the practical challenges of radiation protection policy. These institutional perspectives provide important context for evaluating current regulatory frameworks.

As noted below, there are widely varying opinions within the health-physics community regarding biological response and effects within the low dose region, with none resulting in a definitive scientific consensus. In most instances, these reports and studies have concluded with recommendations to conduct additional research. Institutions such as the ICRP have routinely promoted reductions in occupational dose limits, and whether intended or not, the outcomes have yielded an increasing demand for radiological workers because of artificially restrictive occupational dose limits, such as the current 2 rem per year standard. Although ICRP documents have been relied on to inform portions of U.S. regulations, both the NRC and DOE have not accepted the most-recent dose-limit recommendations from March 2007 contained in ICRP-103. This publication unambiguously states that the "central assumption of a linear dose–response relationship for the induction of cancer and heritable effects, according to which an increment in dose induces a proportional increment in risk even at low doses, continues to provide the basis for the summation of doses from external sources of radiation and from intakes of radionuclides." While the improved dose coefficients in ICRP-103 represent a vast improvement over ICRP-68, the overly restrictive dose-limit recommendations have not been implemented within the U.S. because they would significantly impact current nuclear operations and hinder the promotion of domestic nuclear energy.

2.3.1. Health Physics Society

The HPS has adopted one of the most-explicit positions questioning the LNT model at low doses. In their position statement, PS010-4, "Radiation Risk in Perspective" (2019),[54] the HPS unequivocally states that "below levels of about 100 mSv [i.e., 10,000 mrem] above background from all sources combined, the observed radiation effects in people are not statistically different from zero." This declarative statement directly challenges regulatory frameworks based on the assumption that any radiation dose, no matter how small, carries proportional risk. The HPS further emphasizes that "For radiation protection purposes and for setting radiation exposure limits, current standards and practices are based on the questionable premise that any radiation dose, no matter how small, could result in detrimental health effects such as cancer or heritable genetic damage. Implicit in this [LNT] hypothesis is the core assumption that detrimental effects occur proportionately with radiation dose received (NA/NRC 2006). However, because of statistical uncertainties in biological response at or near background levels, the LNT hypothesis cannot provide reliable projections of future cancer incidence from low-level radiation exposures (NCRP 2001)."

Building on the HPS position, Scott[85] has advocated for "a new low-dose-radiation risk assessment paradigm—one that acknowledges hormesis—and has proposed an alternative framework that better aligns with observational data from occupational and environmental studies. Scott's perspective represents an emerging scientific viewpoint that not only questions the LNT model, but suggests its replacement with a fundamentally different approach to radiation protection. While this position may not be reflective of current radiobiological science, it is accepted that at very low doses the risk is low to zero regardless of radiation response model used.

From a recent publication[86] titled, "Rethinking a tenet of cancer risk assessment for low radiation doses," leaders from the HPS state "Science isn't perfect, but it does theoretically correct itself, and in the process even overturns keystones to fields of knowledge. However, such shifts do not occur without pushback, especially from individuals and organizations with something to protect. While not universally accepted as fact, the Health Physics Society, which is dedicated to radiation safety, produced a documentary that exposes a history of scientific errors, profound bias, professional self-interest, and scientific misconduct that established the fundamental tenet of cancer risk assessment for low doses of radiation where most people live and work." And "Leadership within the HPS strongly encourages an urgent review of the LNT model after carefully examining how it came to be considered akin to scientific dogma." This report understands that this perspective is not universally shared, and as presented throughout, this issue is recognized as a contentious one. To ensure balance, it is necessary to acknowledge that there are countervailing views.[87,88]

2.3.2. International Commission on Radiological Protection

While maintaining the LNT model as the basis for radiation protection recommendations, the ICRP has introduced important qualifications that suggest scientific uncertainty. In Publication 103, the ICRP acknowledges that "the adoption of the LNT model combined with a judged value of a dose and dose-rate effectiveness factor (DDREF) provides a prudent basis for the practical purposes of radiological protection, i.e., the management of risks from low-dose radiation exposure." This carefully worded statement suggests that the ICRP views the LNT model primarily as a practical tool for radiation management, rather than an established scientific fact. The phrase "prudent basis" particularly indicates a precautionary approach that may exceed what is strictly required by the scientific evidence.

Differing perspectives exist on the implications of the ICRP's cautious stance. Allison,[89] in "Radiation and Reason," argues that this approach has fostered a disproportionate fear of radiation that bears little relationship to actual risks and imposes significant societal costs through excessive regulation. In contrast, Valentin[90] offers a more-nuanced defense of the ICRP's position, exploring both the scientific and practical challenges involved in extrapolating radiation-related cancer risk to low doses. While acknowledging the limitations in the current evidence base, Valentin explains why international radiation protection bodies continue to support the LNT model as a prudent approach, despite ongoing scientific debate and uncertainty.

2.3.3. United Nations Scientific Committee on the Effects of Atomic Radiation

United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) has expressed notable skepticism about applying the LNT model to very low doses. Their 2012 report[37] explicitly states that "the Committee does not recommend multiplying very low doses by large numbers of individuals to estimate numbers of radiation-induced health effects within a population exposed to incremental doses at levels equivalent to or lower than natural background levels." This statement directly challenges a common regulatory practice based on the LNT model—the calculation of collective dose and associated population health risks from very low individual exposures. By discouraging this practice, UNSCEAR implicitly questions whether the linear extrapolation of risk to very low doses has scientific validity.

2.3.4. National Council on Radiation Protection and Measurements

The NCRP has taken a more-measured position that acknowledges both the continued utility of the LNT model and its potential limitations. In Commentary No. 27,[91] the Council states that "the shape of the dose-response relationship and the level of risk from low-LET radiation at low doses and/or low dose rates remain uncertain because of the intrinsic uncertainties in results from the epidemiologic and radiobiological studies of low doses of radiation." This acknowledgement of empirical limitations is balanced by their conclusion that "based on current epidemiologic data, the LNT model [perhaps with excess risk estimates reduced by a dose and dose-rate effectiveness factor (DDREF) or a DREF] should continue to be used for radiation protection purposes." In describing the implications of this conclusion, they state that "while the LNT model is an assumption that likely cannot be scientifically validated by radiobiologic or epidemiologic evidence in the low-dose range, the preponderance of epidemiologic data is consistent with the LNT assumption, although there are a few notable exceptions. The current data are not precise enough to exclude other models, and there appears to be curvature in some datasets. The current judgment by national and international scientific committees is that no alternative dose-response relationship appears more pragmatic or prudent for radiation protection purposes than the LNT model on the basis of available data, recognizing that the risk <100 mGy is uncertain but small." This position preserves the LNT model while acknowledging the possibility that actual risks at low doses could be substantially lower than predicted by linear extrapolation.

2.3.5. National Academy of Sciences/BEIR VII

The BEIR VII report,[13] while it supports the LNT model, also recognizes the statistical limitations of epidemiological studies at low doses. The report acknowledges that at doses less than 10,000 mrem, "statistical limitations make it difficult to evaluate cancer risk in humans." This statement aligns with the observations of other organizations regarding the practical challenges of directly measuring radiation effects at dose levels relevant to most occupational and public exposures. Despite these acknowledged limitations, the BEIR VII report has been influential in maintaining the regulatory status quo because it ultimately endorses the continued use of the LNT model for radiation protection purposes.

Collectively, these positions from major professional organizations reveal a nuanced scientific landscape. While most organizations maintain some version of the LNT model for practical radiation protection purposes, there is widespread acknowledgment of its limitations and growing recognition that risks at low doses may be significantly lower than predicted by simple linear extrapolation from high-dose data. This evolving scientific consensus provides an important foundation for reconsidering current regulatory approaches to better align with contemporary understanding of radiation health effects.

3. EPIDEMIOLOGICAL EVIDENCE

Epidemiological research investigates the distribution, patterns, and determinants of health and disease conditions in a population. It aims to identify risk factors, understand disease transmission, and develop strategies for prevention and intervention.

3.1. Limitations of Epidemiological Studies

Epidemiological studies examining radiation's health effects confront several significant methodological challenges that warrant careful consideration when interpreting their findings. Statistical power becomes increasingly limited at lower doses, where potential health effects, if present, may be too small to detect against background cancer rates. This challenge is compounded by numerous confounding factors—socioeconomic status, smoking habits, and other lifestyle variables—that can mask or amplify apparent radiation effects. Historical dosimetry uncertainties further complicate accurate exposure assessment, particularly in retrospective studies. Additionally, extrapolating risk estimates from high-dose data to low-dose scenarios introduces substantial uncertainty while the "healthy worker effect" in occupational studies (where employed populations typically demonstrate better overall health than general populations) can obscure radiation-related health impacts.

Sacks et al.[92] provide a comprehensive critique of these methodological limitations, arguing that many epidemiological studies in radiation science suffer from "false paradigms, unfounded assumptions, and specious statistics" that undermine their reliability for low-dose risk assessment. Their analysis suggests that the foundation for current radiation protection standards may rest on methodologically questionable research that fails to adequately account for these limitations.

However, the scientific community remains divided on how to interpret these limitations. Little et al.[93] contend that despite acknowledged methodological challenges, the weight of evidence from existing epidemiological studies continues to support the LNT model. They argue that "linearity may be (almost) the best we can do" when modeling radiation risks at low doses, suggesting that when multiple lines of epidemiological evidence are considered together, the data remain broadly consistent with an LNT relationship. This ongoing scientific debate underscores the importance of critically examining the strengths and weaknesses of available evidence when evaluating radiation protection frameworks.

3.2. Major Epidemiological Studies

3.2.1. Life Span Study of Atomic-Bomb Survivors

The Life Span Study of Japanese atomic-bomb survivors provides the primary foundation for current radiation-risk estimates worldwide. This extensive research demonstrated significant excess relative risk (ERR) for solid cancers at acute doses exceeding 10,000–20,000 mrem.[38,42] However, at doses below 10,000 mrem, the statistical significance becomes limited. This distinction is critically important when considering radiation protection standards. Notably, radiation protection authorities recommend applying a DREF of 1.5–2 when extrapolating from these acute high-dose exposures to the chronic low-dose scenarios typically encountered in occupational settings. This adjustment acknowledges a fundamental limitation of the Life Span Study data: it documents health effects from intense, instantaneous radiation exposure—an acute exposure scenario fundamentally different from the chronic low-dose exposures experienced by radiation workers or the public near nuclear facilities.

3.2.2. Nuclear Worker Studies

Several major cohort studies have investigated cancer risks among nuclear-industry workers, offering valuable insights into chronic occupational exposures. The International Nuclear Workers Study (INWORKS) reported statistically significant ERR for leukemia (excluding chronic lymphocytic leukemia) and solid cancers combined,[20] calculating an ERR per Gy of 0.47 for solid-cancer mortality. This finding appears to support radiation effects at lower doses. However, other major studies—including the 15-Country Study[21] and the UK's National Registry for Radiation Workers[22]—found effects that were only marginally significant, highlighting inconsistencies in the literature.

These nuclear-worker studies face substantial methodological challenges. Lifestyle confounders such as smoking habits often remain unaccounted for, and historical dosimetry methods introduce significant uncertainty in exposure estimates. Despite these limitations, more-recent analyses from the INWORKS cohort by Leuraud et al.[94] suggest a positive association between protracted low-dose radiation exposure and leukemia mortality, with ERRs potentially compatible with models derived from high-dose exposure studies. Richardson et al.[20] reported similar findings for solid-cancer risks in the same cohort, noting a statistically significant association between cumulative radiation dose and solid-cancer mortality, even at the low-dose rates common in occupational settings. These findings have been interpreted by some researchers as supporting the continued use of the LNT model for radiation protection purposes.

3.2.3. High Natural-Background-Radiation Areas

Studies of populations living in regions with naturally elevated background radiation provide a unique opportunity to examine chronic radiation exposure effects outside experimental or occupational contexts. In Yangjiang, China, where background radiation averages 640 mrem annually (approximately three times higher than control areas receiving 210 mrem annually), researchers have not identified statistically significant increases in cancer risk.[17] Similarly, investigations in Kerala, India, where background radiation reaches up to 7,000 mrem annually, have not demonstrated clear evidence of increased cancer rates.[18]

Perhaps most striking are studies from Ramsar, Iran, which experiences some of the highest natural-background-radiation levels worldwide—reaching up to 26,000 mrem annually in some localities. Despite these extraordinary exposure levels, researchers have not found conclusive evidence of adverse health effects among residents.[19] A comprehensive analysis extensively documents conditions in this area, reporting that despite lifetime radiation exposures far exceeding international occupational limits, no adverse health effects have been conclusively demonstrated among the local population. Collectively, these studies of areas with high natural background radiation suggest that chronic exposure to elevated radiation levels may not produce detectable increases in cancer risks. This analysis challenges fundamental assumptions of current radiation protection frameworks, and while not meant to be definitive, they certainly cannot be dismissed when evaluating the effects of significant doses received by a substantial cohort that do not fully comport to the theory that all responses can result in negative health effects. This issue was addressed by Hendry et al and they cautioned against over-interpreting findings in the high-natural-background region, for several reasons cited in their paper.[55]

Background radiation levels have changed throughout Earth's 4-billion-year history. Through geological time the uppermost layers of the crust steadily became enriched in radioactive ^{40}K, U, and Th. In addition to enrichment, radioactive decay reduced the radioactivity concentrations in the crust. The result is that radiation levels from geologic and internal biologic emitters (^{40}K) likely peaked about 2 billion years ago (Ga) at a dose rate of about 700 mrem per year while radioactive decay of ^{40}K reduced radiation dose from internal emitters by a factor of 10 since life first appeared. Coincidentally the radiation dose from galactic cosmic rays has likely increased while the dose from solar charged particles has decreased. Solar ultraviolet emissions have increased, but the formation of the ozone layer (2 billion years ago) has dropped the ultraviolet flux by an estimated factor 400 through time. The rise in atmospheric oxygen levels from 15 to 21% also occurred during this geological period. This period corresponds to the emergence of living organisms on the planet, and the environmental factors above influenced their evolution and likely affected their DNA-damage repair mechanisms given the type of organism and their specific environments (e.g., aerobic vs. anaerobic or photic zone vs. deep marine).

Many DNA-damage repair mechanisms in modern organisms are conservative; they are very similar in widely disparate kingdoms such as eubacteria, archaebacteria, and animalia (the animal kingdom). This observation supports the proposition that such repair mechanisms evolved only once in a common ancestor to all modern life forms, before life diverged to form the modern kingdoms. If this is the case, then the mutation-repair mechanisms in humans likely has its evolutionary roots in an environment that was far more mutagenetic than today's and may have retained that ability to successfully repair levels and rates of DNA damage in excess of those found today. This possibility gives a geological and historical context to the idea of a threshold level, below which life's cellular repair mechanisms can adequately repair radiation damage with little or no expected harmful effects to the organism. The discovery that adaptive response to radiation can be induced by exposure to elevated levels of background radiation, such as those found in Ramsar, Iran, lends credence to this.[95]

3.2.4. Million Person Study

The Million Person Study (MPS)[96] began in the early 2000s and stands as the pioneering and most-extensive research initiative examining how low-dose radiation exposure affected American workers and veterans throughout the 1900s. Unlike previous research focused on Japanese atomic-bomb survivors who experienced brief high-dose radiation in 1945, the MPS was specifically designed to study radiation risks in healthy American populations that better represent contemporary demographics. Researchers plan to continue monitoring the 34 distinct groups within the MPS over the coming decades.[97] The MPS has published more than 80 papers in the peer-reviewed literature, describing an ongoing efforts to evaluate the cohorts, refine the dosimetry, clarify the causes of death, etc.[98] The importance of the MPS relative to other epidemiological studies is that they have obtained dosimetric records and have been able to ensure consistency in organ and whole-body doses. This is important, because ultimately it will allow for pooling of the cohorts (which include nuclear power plant workers, DOE workers, industrial radiographers, medical workers, atomic veterans, radium dial painters and more). Individuals in these cohorts have individual-worker identification attributes making it easier to account for and control for overlaps between these cohorts. This information also includes cross references data from Medicare/Medicaid that provide insight into health conditions. The statistical power of this pooled study far exceeds previously undertaken studies.[99,100]

3.3. Meta-Analyses and Pooled Studies

The field has benefited from several meta-analyses that attempt to synthesize the diverse body of epidemiological evidence. Shore et al.[101] conducted a meta-analysis specifically examining low-dose-rate exposures and derived risk coefficients lower than those derived from atomic-bomb survivors. This finding suggests that chronic exposure at low dose rates may pose less risk than equivalent doses delivered acutely, supporting the application of a dose-rate effectiveness factor in radiation protection.

Perhaps most significant for regulatory considerations, Doss[28] performed a meta-analysis that suggests no increased cancer risk below approximately 10,000 mrem per year. This threshold-like finding directly challenges the fundamental LNT assumption that underpins current radiation protection frameworks that presume risk exists at any dose, no matter how small. If validated through further research, such findings could have profound implications for occupational- and public-dose limits, potentially allowing for substantial regulatory reform while maintaining appropriate safety margins.

These meta-analyses serve an essential function in radiation protection science by integrating evidence across diverse studies with different methodologies, populations, and exposure scenarios. While individual studies may face significant limitations, as outlined earlier, the weight of evidence across multiple studies and various exposure contexts provides a more-robust basis for evaluating dose-response relationships, particularly at the low doses relevant to radiation protection standards.[102,103]

4. RADIOBIOLOGICAL EVIDENCE

Radiobiological research is the study of how radiation interacts with living organisms, from the molecular level to the whole body. It focuses on the effects of radiation, both ionizing and non-ionizing, on cells, tissues, and organisms, with a particular focus on understanding the mechanisms of DNA damage and repair, as well as the biological responses to radiation exposure.

4.1. Cellular Responses to Low-Dose Radiation

Radiobiological research has revealed complex cellular responses to radiation that challenge the LNT model, particularly at low doses. These responses suggest that biological effects may not follow the simple linear relationship assumed by current radiation protection frameworks.

4.1.1. DNA-Repair Mechanisms

Cellular DNA-repair processes demonstrate significantly higher efficiency at low dose rates than at high dose rates.[104] This differential response contradicts a key assumption of the LNT model, which presumes identical damage response regardless of dose rate. Research has further shown that low doses of radiation may actually stimulate repair capacity, potentially enhancing cellular resistance to subsequent damage.[105] This stimulation represents a non-linear response that the LNT model fails to account for in its risk projections.

4.1.2. Adaptive Response

The adaptive-response phenomenon provides compelling evidence against linear risk extrapolation. Studies have demonstrated that prior exposure to low-dose radiation can significantly reduce the biological impact of subsequent higher doses.[106,107] This protective effect suggests that low-dose radiation activates cellular defense mechanisms that would otherwise remain dormant.[108] Feinendegen and colleagues have documented these adaptive responses in detail, describing how low-dose radiation exposure stimulates enhanced DNA repair, activates immunological responses, and increases antioxidant production. These protective mechanisms appear most effective at the very dose ranges relevant to occupational exposures, suggesting that the LNT model's risk projections in this range may overestimate actual biological harm.

4.1.3. Bystander Effects and Genomic Instability

An emerging challenge to traditional radiation dose-response models comes from the theory of non-targeted effects that occur in cells not directly hit by radiation. These so called "bystander" effects occur when irradiated cells communicate with neighboring non-irradiated cells through intercellular signaling mechanisms.[108] The irradiated cells release signaling molecules, including cytokines and reactive oxygen species, that trigger responses in bystander cells that received no direct radiation. This observation was observed primarily in adjacent cells with cellar damage from previous radiation exposure. These non-irradiated cells can subsequently exhibit DNA damage, chromosomal aberrations, altered gene expression, apoptosis, and cellular transformation. Remarkably, these bystander effects have been observed at radiation doses so low that direct DNA damage would be minimal or even nonexistent in the affected cells.

These communication pathways appear to operate through both direct cellular contact via gap junctions and through medium-mediated factors.[104,108] These bystander effects may produce non-linear dose responses, suggesting that the LNT model cannot adequately capture the complexity of cellular responses to low doses of radiation.

Genomic instability represents another non-targeted effect with potential implications for radiation protection. This phenomenon describes elevated rates of genetic alterations appearing in the progeny of irradiated cells many generations after the initial exposure. Unlike direct radiation damage, these effects emerge only after multiple cell divisions, manifesting as increased rates of mutation, chromosomal abnormalities, micronuclei formation, altered gene expression, and delayed cell death. This transgenerational effect indicates that radiation can induce long-lasting changes to cellular regulatory processes that extend well beyond immediate DNA damage. Like bystander effects, genomic instability has been documented after exposure to very low radiation doses.[108] It should be noted that more far-reaching, intergenerational studies of atomic-bomb survivors do not show any heritable effects that would support this theory.

These observed phenomena fundamentally challenge the LNT model by demonstrating non-linear dose-response relationships. Both effects show unexpected responses at low doses than would be predicted by simple linear extrapolation from high-dose data. This extrapolation originated with bomb survivors, and it was noted that, at doses below 10,000 mrem, there were no observable health effects. Further extrapolation of acute doses formed the basis for current annual dose limits. In some scenarios, bystander signaling actually triggers protective mechanisms that potentially lead to adaptive responses or beneficial effects at low doses. The existence of these complex cellular-communication pathways means that risk calculations cannot be based solely on direct DNA hits, as the LNT model assumes. Some research suggests these effects may exhibit threshold-like behavior, where below certain doses, the effects change qualitatively, not just quantitatively.[104,108] This latter theory recognizes the ubiquitous nature of radiation exposure to all population groups.

While the implications of these effects for low-dose radiation protection remain an active area of research, they clearly demonstrate that cellular responses to radiation are more complex than simple linear models suggest. As Calabrese[109] notes in his comprehensive assessment, the historical foundations of the LNT model were not based on robust scientific evidence; rather, they were based on theoretical assumptions that have since been challenged by radiobiological research.

In light of these studies and varying opinions within the health-physics community, pragmatic dose constraints have been established within a regulatory framework within the low-dose region where the responses are not clear and, depending on interpretation, can sometimes appear to be contradictory. This report recognizes these facts and advocates maintaining dose constraints within this region while scientific inquiry continues. The overarching question then becomes do these models remain useful in the dose region of interest?[110] More-recent reviews of activity in the low dose rate research[111] as well as the work by Laurier et al., argue that the current status of scientific knowledge does not contradict the use of LNT.[112]

4.2. Threshold Models and Hormesis

The growing body of radiobiological evidence has led researchers to propose alternative models to the LNT hypothesis. Threshold models suggest that radiation effects only manifest above certain dose thresholds, below which no adverse health impacts occur. More controversial are hormesis models, which posit that low doses of radiation may actually produce beneficial effects through stimulation of repair mechanisms and immune responses.[113,114]

Laboratory studies have demonstrated radiation hormesis in various biological systems, with some research showing increased longevity in irradiated organisms compared to non-irradiated controls.[115] Sanders[116] has compiled extensive evidence supporting radiation hormesis and argues that the scientific basis for the LNT assumption is fundamentally flawed when considering the totality of biological responses to low-dose radiation.

However, the scientific community remains divided on these alternative models. Critical analyses of hormesis research[117] urge caution in interpreting these results, noting that many hormesis studies suffer from methodological limitations, including inadequate controls, statistical issues, and problems in experimental design. Hendry et al.[55] acknowledge the value of studies in high natural-background-radiation areas, but observe that they have not provided consistent evidence for hormesis effects in human populations. They emphasize that even if adaptive responses exist, they may not completely eliminate cancer risk at low doses. Puskin[118] maintains that the totality of evidence remains most consistent with a LNT response, even while acknowledging that cellular-repair mechanisms may modify the dose-response relationship at very low doses.

The scientific literature is full of discussions about a variety of radiation responses in the low- and very-low-dose regions. The LNT model was selected on what was argued at the time to be a pragmatic approach that attempted to seek a balance between potential risk and keeping exposures reasonably low. However, over time this has transformed into a drive towards zero without regard to impact, cost, or benefit. The purported pragmatic approach is now a significant burden without benefit. Several scholarly articles delve into different cellular responses in the region, such as the role of mitochondria in radiation responses. The authors note the many responses that can occur in the low dose region, including potentially hormetic responses. However, they also noted that ionizing radiation appears in certain situations to stimulate cancer-cell response.[119] This report seeks to address what is the most-pragmatic response to managing doses in the <100 mGy (i.e., the <10,000 mrad) region. In 2006, Brenner and Sachs provided a good dissertation on this topic.[120]

5. HEALTH EFFECTS ASSOCIATED WITH DIFFERENT EXPOSURE SCENARIOS

5.1. Nuclear-Weapons Exposures

Beyond the atomic-bomb survivors discussed previously, studies of other populations exposed to nuclear-weapons testing provide additional insights into radiation's health effects. Research on Marshall Islanders exposed to nuclear testing fallout has documented increased thyroid disease at doses exceeding 10,000 mrem, but effects at lower doses remain uncertain and difficult to quantify.[121] Studies of downwind populations near the Nevada Test Site have suggested some evidence of increased leukemia risk, though these findings are limited by significant methodological challenges in dose reconstruction and confounding factors.[122] Parsons and Townsend[123] have contributed valuable analyses of radiation-exposure scenarios from space and nuclear events that can inform safety-margin considerations for terrestrial occupational exposures.

5.2. Medical Exposures

Medical radiation exposures offer particularly valuable insights due to their well-characterized doses and extensive follow-up data. Multiple CT scans in childhood have been associated with increased cancer risk, but typically only at cumulative doses exceeding 5,000–10,000 mrem.[23] An important consideration when evaluating cancer risk from medical exposures is the reason behind the medical scan (e.g., pediatric cancer and known radiosensitivity within this cohort).[124] Radiotherapy patients who receive partial-body exposures show increased second-cancer risks, but at doses far exceeding occupational limits, typically above 100,000 mrem.[24] Importantly, diagnostic nuclear-medicine procedures at doses below 10,000 mrem have not been conclusively linked to increased cancer risks.[25] Historical use of radiotherapy for non-malignant conditions like pneumonia demonstrated both therapeutic benefits and later risks at various dose levels, with the risk-benefit balance shifting depending on dose.[125] Total-body irradiation techniques developed for lymphoma treatment have further informed scientific understanding of whole-body radiation effects.[126]

Recently, the NCRP issued Recommendations for Ending Routine Gonadal Shielding During Abdominal and Pelvic Radiography NCRP Statement No. 13, January 12, 2021.[127] Presently, the NCRP, through its Scientific Committee SC 4-13, is looking at the issue of patient shielding in medical imaging—where the need to obtain useful medical images is balanced against extraneous dose. This committee uses the concept "as low as appropriate," rather than ALARA for the patient, and the net result often means giving a slightly higher dose or not shielding particular body parts (even for pediatric patients) in order to ensure that adequate image quality is produced.

Siegel and colleagues[128] argue that the NRC's regulatory guidelines on patient release after radioiodine treatment are overly conservative, place unnecessary burdens on patients and medical facilities, and fail to align with scientific understanding of radiation effects, supporting the case for regulatory reform in medical applications of radiation. Siegel and colleagues[129] further argue that subjecting radiological imaging to LNT-based policies represents a non-evidence–based approach to radiation protection that may unnecessarily limit beneficial medical procedures.

5.3. Nuclear Accidents

Population studies following nuclear accidents provide an additional source of data on radiation health effects. After the Chernobyl accident, increases in thyroid cancers were observed in children, but primarily at doses exceeding 10,000 mrem.[130] The UNSCEAR 2008 report, specifically Annex D, summarizes the health effects of radiation from the Chernobyl accident. Apart from a significant increase in thyroid cancer cases, particularly among those exposed as children, the report found no clear evidence of other major public health impacts related to radiation exposure. However, there were widespread psychological reactions due to fear of radiation, not necessarily from the actual radiation doses.[131] Studies

of emergency workers at Chernobyl who received higher doses demonstrate increased leukemia risk, but findings at doses below 10,000 mrem remain inconclusive.[132] Jaworowski[133] has provided a critical assessment of Chernobyl data interpretation, arguing that many health effects attributed to radiation exposure were more likely consequences of psychological stress, relocation trauma, and excessive application of the LNT model, which led to unnecessary evacuations and social disruption.

Early data from the Fukushima accident suggest no detectable health effects at the population level, with most civilian exposures remaining below 2,500 mrem.[134] A study of evacuated residents concluded that the psychological trauma of evacuation was a bigger health risk for most than any likely exposure from early return to homes.[135,136] When managing an event in which the exposures have the potential to be very large, such as Fukushima—where initially it was thought the potential for much greater release was imminent—a balance had to be developed for just how much dose emergency responders would potentially receive. Subsequent reviews of mortality in evacuated patients showed elevated rates relative to others.[137]

Long-term follow-up studies of nuclear-accident victims have helped refine dose-response relationships for various cancer types, though substantial uncertainties remain, particularly at lower doses.

5.4. Elevated Natural Background Radiation

As discussed in the section on epidemiological evidence, studies of populations living in areas with elevated natural background radiation have generally not demonstrated conclusive evidence of adverse health effects at dose rates comparable to or exceeding the 5,000-mrem U.S. occupational limit. Additional studies of natural background radiation in the U.S. have shown regional variations in cancer rates that do not correlate with background radiation levels.[138] The lack of correlation in this study and others (e.g., 17,18,19) challenges the fundamental assumption that cancer risk increases linearly with radiation dose at all exposure levels.

A thorough literature review of high natural-background-radiation area studies noted that “most of these studies have concluded that there is no link between exposure to high background natural radiation and an increased rate of cancer or mortality. However, the results of these studies should be considered with caution because of the confounding factors associated with their methodology.”

As noted in the two paragraphs above, controlling for confounding factors is essential to determining more-precise radiation responses in varying low dose areas.

6. EVIDENCE FOR POTENTIAL HEALTH BENEFITS OF LOW-DOSE RADIATION

While conventional radiation protection frameworks are predicated on the assumption that any radiation exposure carries proportional risk, a growing body of scientific evidence suggests the possibility that low-dose radiation may actually confer certain health benefits—a phenomenon known as radiation hormesis. This controversial area of research challenges fundamental assumptions of current regulatory approaches and merits careful examination.

6.1. Radiation Hormesis Research

Multiple lines of scientific inquiry have generated evidence supporting potential beneficial effects from low-dose radiation exposure. Animal-model studies have demonstrated increased longevity in organisms exposed to low-dose radiation compared to non-irradiated controls.[113,115] These findings suggest that, rather than shortening lifespan, as would be predicted by the LNT model, low-dose radiation may activate biological mechanisms that enhance overall health and longevity under certain conditions.

At the cellular level, research has revealed enhanced repair mechanisms and increased antioxidant production following low-dose radiation exposure.[105,114] These cellular responses appear to represent adaptive mechanisms that can strengthen the cell's resistance to subsequent damage from various stressors, not limited to radiation. This adaptive response aligns with broader biological principles of hormesis, where low doses of a potentially harmful agent can stimulate beneficial compensatory biological responses.

Some epidemiological studies of regions with elevated natural background radiation have occasionally reported lower cancer rates than control regions with normal background levels.[138] While these findings remain controversial and require further validation, they suggest that chronic exposure to low-dose radiation may not increase cancer risk as predicted by the LNT model, and might potentially provide protective effects under certain circumstances.

The concept of radiation hormesis itself has a complex scientific history, as documented by Calabrese and Baldwin.[113] Their historical analysis demonstrates that the radiation-hormesis hypothesis actually predates the LNT model, but was marginalized during the development of radiation protection standards despite significant supporting evidence. This marginalization may have resulted more from policy considerations and the precautionary principle than from decisive scientific evidence against hormesis.

6.2. Immunological Effects

Particularly intriguing are studies suggesting that low-dose radiation may enhance immune function, potentially improving the body's natural defense mechanisms. Liu[139] demonstrated enhanced T-cell activity following low-dose radiation exposure, indicating improved cellular immune response. Additional research has shown that low-dose radiation can stimulate natural killer-cell activity, another critical component of the immune system's surveillance against cancer cells and pathogens.[140] These immunological effects suggest potential mechanisms through which low-dose radiation might reduce cancer risk or enhance resistance to disease, contrary to conventional radiation protection assumptions.

6.3. Therapeutic Applications

Perhaps the most-direct evidence challenging the assumption that all radiation exposure is harmful comes from the therapeutic applications of low-dose radiation. Low-dose total body irradiation has shown efficacy in treating certain lymphomas,[126] demonstrating that radiation can be harnessed beneficially even when exposing the entire body. It should be noted here that these treatments entailed receiving 150 rad to the tumors, these types of highly localized doses still fall well within the defined low-dose region (<10 rem) because total whole-body dose is not measured solely by localized exposures.[141] Historical medical practices included the use of low-dose radiation for treating various inflammatory conditions, with documented benefits for patients.[125] These historical applications fell out of favor, not necessarily because they were ineffective, but largely due to changing medical paradigms and the emergence of pharmaceutical alternatives.

Cuttler[142] has provided a comprehensive review of applications of low doses of ionizing radiation in medical therapies, documenting numerous cases where low-dose radiation has been successfully used to treat various conditions. His analysis directly challenges the assumption that all radiation exposure is inherently harmful and suggests that appropriate doses may be beneficial in specific medical contexts. Yang and colleagues[140] have further suggested that low-dose radiation may enhance the effectiveness of cancer therapeutics through immune-system stimulation and other biological mechanisms, pointing to potential synergistic applications in modern oncology. Current radiation-therapy modalities continue to see the application of a range of doses to treat a variety of conditions, balancing risk and benefit to achieve tumor control or pain management. This is a standard practice in the use of hypofractionated—that is, fewer fractions, but larger doses—radiotherapy for breast cancer.

However, the scientific community remains divided on these potential benefits. While the evidence suggesting potential benefits of low-dose radiation continues to accumulate, this remains a controversial area requiring further investigation through rigorous research designs. The possibility of beneficial effects does not negate the need for prudent radiation protection measures, but it does raise important questions about whether current regulatory frameworks, based exclusively on the LNT model, accurately reflect the full spectrum of biological responses to radiation across different dose ranges.

7. ECONOMIC AND PRACTICAL IMPLICATIONS

7.1. Costs of Current Regulatory Approach

Although the economic and operational consequences of the current regulatory approach have not been comprehensively quantified for many applications, they are widely understood to be significant. The current radiation protection frameworks in the nuclear industry impose numerous additional requirements, including engineering, design, operational, and administrative controls and training requirements, that have substantial cost and time impacts, particularly due to the implementation of ALARA principles below regulatory limits. This burden has increasingly prompted questions about cost-effectiveness when compared to other public health and safety investments. The limited studies examining the economic efficiency of radiation protection measures have suggested that the cost per life saved through nuclear-industry safety protocols can be exceptionally high relative to interventions in other sectors, raising fundamental questions about optimal resource allocation in public-health policy. Research by Cohen[143] estimated that the cost per life saved through nuclear industry radiation protection measures exceeds $2.5 billion at dose levels below 1,000 mrem per year, which is substantially higher than the $10–15 million per life saved typically considered cost-effective in other public-health and safety domains, according to standards established by agencies such as the U.S. Department of Transportation and the Environmental Protection Agency.[144,145,146]

Economic perspectives on these costs vary considerably. Some analysts maintain that the high expenditures represent an inefficient use of resources that could provide greater public-health benefits elsewhere. In an earlier study, Cohen[147] concluded that "safety expenditures in excess of a few hundred dollars per man-rem of exposure avoided cannot be considered cost effective" compared to other health interventions. Mubayi et al.[148] conducted a comprehensive review of factors affecting the valuation of averted radiation dose and assessed the continuing validity of the figure of $1000/person-rem averted, which has been widely used as a guideline in performing value-impact analyses for nuclear safety enhancements. Others, such as Shrader-Frechette,[149] contend that economic assessments of radiation protection often fail to properly account for all societal costs associated with radiation exposures, particularly long-term health effects and environmental-justice concerns. These contrasting viewpoints reflect the ongoing debate about whether current radiation protection strategies strike the right balance between precaution and economic efficiency.

In countries like Sweden, specific cost thresholds have been established for radiation protection measures. According to their framework, if the marginal cost for a protective measure is less than 5 million Swedish crowns (approximately $1 million USD) per prevented case, the radiation protection authority considers the measure to be strongly justified while costs exceeding 25 million Swedish crowns require "very strong reasons" for implementation.[150]

It should be noted that comprehensive economic analyses associated with radiation protection requirements are limited in the literature, making it difficult to establish definitive conclusions about the overall cost-benefit relationship of current protection frameworks.

7.2. Economic Impact Across Nuclear Industries

7.2.1. Nuclear Power Generation

The financial impact of radiation protection requirements on nuclear power generation is significant and multifaceted. Under the current regulatory approach—which maintains the 5,000 mrem/year occupational exposure limit while implementing ALARA principles—nuclear plants face substantial costs across multiple operational areas.

In the energy sector, regulatory requirements influence the economics of nuclear power generation. Wheatley et al.[151] examined how safety regulations, including radiation protection measures, contribute to the overall cost structure of nuclear energy. The World Nuclear Association notes that regulatory frameworks are among several factors affecting nuclear power's competitiveness in prioritizing affordable, reliable, and secure energy.[152]

These costs manifest in several key areas: specialized radiation protection personnel and training programs, sophisticated radiation-monitoring equipment and dosimetry systems, protective equipment and clothing, shielding materials and infrastructure, and extensive administrative-compliance and reporting requirements. These overly restrictive radiation-related regulatory requirements significantly influence the cost of design and implementation of new advanced research and power reactors to ensure ALARA objectives are met. This increases costs for planning, engineering design and analysis, additional materials for shielding, automation, etc.

The operational impacts of these requirements are equally significant. Worker-rotation policies implemented to limit individual radiation doses increase staffing requirements for certain maintenance operations. Additional outage time dedicated to dose management can substantially impact plant economics through loss of generation revenue. These operational constraints, while designed to enhance safety, contribute to the overall economic challenges facing nuclear power generation. Specific regulatory measures also provide insight into the scale of these expenditures, and the likely large magnitude of radiation regulatory cost. For example, the NRC's "Fitness for Duty" requirements, which include worker health and safety components, were estimated to cost the industry $481 million overall.[153] Similarly, post-9/11 security requirements, which incorporate radiation protection elements, were estimated at $154 million for the industry, with $38 million in annual costs.

While comprehensive and current figures specifically for per-plant radiation protection implementation costs are not widely documented in public literature, these data points collectively illustrate the significant economic implications of radiation protection requirements on nuclear-power economics. As the industry continues to face competitive pressures from other energy sources, the balance between safety requirements and economic viability remains a critical consideration for the future of nuclear power.

7.2.2. Nuclear-Waste Disposal and Cleanup

Beyond nuclear-power operations, radiation protection requirements also significantly impact environmental-cleanup costs at former U.S. nuclear-weapons development sites, which represent some of the largest and most-expensive environmental-remediation projects in the world, with total project costs

ranging from $675 billion to $900 billion through the latter part of this century, according to a recent Government Accountability Office (GAO) report.[154]

A related GAO report[16] states,

> *The costs of implementing different radiation standards vary, depending on the standards' restrictiveness. Generally, the costs increase as the standards become more restrictive. Comprehensive estimates of overall costs to comply with current and prospective standards were unavailable, but these costs could be immense, considering that federal agencies expect to fund hundreds of billions of dollars in nuclear-waste disposal and cleanup projects over many years in the future. According to DOE's and NRC's analyses of cleanup options for individual sites, costs per site can be many millions of dollars higher to comply with more restrictive standards than less restrictive standards, as might be expected. For example, a 1995 DOE analysis of cleanup options for plutonium-contaminated test ranges at the Nevada Test Site estimated $35 million in costs to achieve a 100-millirem-a-year-level, over three times as much to achieve a 25-millirem-a-year level, and over six times as much to achieve a 15-millirem-a-year level. Finally, the analysis showed costs that were over 28 times higher to achieve a 5-millirem-a-year level, illustrating that compliance costs accelerate rapidly to achieve the most restrictive protection levels.*

These requirements also impact commercial spent-nuclear-fuel storage, transportation and disposal. Given the large cost associated with spent-nuclear-fuel management and disposal, the benefits could be immense for that as well. For national interim storage and the proposed repository at Yucca Mountain, the GAO estimated "the 2009 present value cost of on-site storage of 153,000 metric tons at the end of 100 years to range from $13 billion to $34 billion but increasing to between $20 billion to $97 billion with final geologic disposal."[155] Another consideration associated with the extremely restrictive cleanup standards, in addition to being costly, are frequent delays related to site access or reuse. These delays can contribute to community suspicion because expected reuse and availability of exceptional real-estate properties that could be used to the benefit of the community are denied.

7.2.3. Nuclear Medicine and Medical Applications

Medical applications of radiation face economic and practical challenges under current regulatory frameworks. While comprehensive studies specifically quantifying facility-wide radiation protection compliance costs are limited, the available literature indicates these measures constitute a significant operational consideration in nuclear-medicine departments.

Miller et al.[29] examined radiation-dose management practices in interventional radiology, highlighting the resource implications of implementing comprehensive radiation protection measures. Their research underscores the multifaceted nature of radiation-safety compliance, which encompasses personnel monitoring, equipment quality assurance, and specialized facility-design considerations.

A review by Zanzonico and Stabin highlights the complex balance between radiation protection and healthcare delivery, noting that excessive regulatory conservatism may impact operational efficiency without proportional safety benefits.[30] These regulatory considerations affect workflow, staffing requirements, and infrastructure design in nuclear-medicine facilities.

Research by Siegel, Pennington, and Sacks argues that radiation protection policies based on the LNT hypothesis may lead to suboptimal resource allocation in medical settings.[129] Their analysis suggests that regulatory approaches not accounting for potential thresholds in radiation response could impose operational constraints that affect healthcare delivery without commensurate health benefits.

Marcus has further advocated for regulatory reform, proposing that threshold-based approaches to radiation protection could maintain safety while potentially reducing compliance burdens.[156] This perspective suggests that modified regulatory frameworks might enable more-efficient utilization of medical radiation resources while maintaining appropriate safety standards.

Regarding patient-release criteria following radioiodine treatment, Siegel, Marcus, and Stabin demonstrated that overly conservative interpretations of NRC guidance may unnecessarily extend hospital stays.[128] Their analysis indicates that more scientifically justified approaches to patient release could reduce healthcare costs and improve resource utilization while maintaining public safety.

Radiation protection considerations can also influence medical decision-making and procedure availability. Fazel et al. documented how radiation-dose concerns factor into clinical decisions regarding imaging procedures, potentially affecting patient-care pathways.[157] Similarly, Hendee and O'Connor discussed how radiation-safety protocols, while essential for protection, require careful implementation to avoid unnecessarily limiting beneficial medical procedures.[158]

The debate surrounding radiation protection optimization in medical settings continues to evolve, with ongoing research examining how regulatory frameworks might balance safety, operational efficiency, and healthcare accessibility. However, specific quantitative estimates of potential cost savings or operational improvements from regulatory modifications would require additional research to establish with scientific validity.

7.2.4. Industrial Radiography and Other Applications

Non-power industrial applications of radiation also face notable economic impacts from current radiation protection requirements. Radiation protection measures constitute a significant operational consideration for industrial-radiography companies, affecting both operational practices and resource allocation (IAEA Safety Reports Series No. 13).[32] Industrial-radiography operations must balance radiation-safety requirements with operational efficiency, which influences staffing approaches, equipment selection, and project planning. The implementation of dose-management practices, including worker rotation and monitoring, represents an operational factor that impacts workforce utilization and project scheduling.

According to ICRP Publication 103, radiation protection optimization involves economic considerations alongside safety factors. The ICRP acknowledges that protection measures have associated costs that should be evaluated in proportion to their safety benefits, suggesting a balanced approach to regulatory implementation.

The NCRP examined operational aspects of radiation protection in industrial settings, noting that compliance with regulatory requirements involves both direct (equipment, monitoring devices) and indirect costs (training, administrative procedures).[50] These factors collectively influence operational strategies for industrial-radiography service providers.

While specific quantification of regulatory impact on operational budgets varies across different operational contexts and facility sizes, the literature consistently recognizes that radiation protection requirements are a meaningful factor in operational planning and resource allocation for industrial-radiography operations. Any theoretical modifications to regulatory approaches would need careful evaluation to balance potential operational efficiencies with the primary objective of ensuring appropriate radiation safety for workers and the public.

7.3. Broader Implications for Nuclear Technology and Society

Radiation protection standards have implications that extend beyond direct economic costs, affecting energy production, healthcare delivery, and public perception of nuclear technologies.

Regarding public perception, research by Slovic has established that a significant gap exists between public perception of radiation risks and scientific risk assessments.[159] This perception discrepancy can influence social acceptance of nuclear technologies. Fischhoff demonstrated that how risks are communicated significantly affects public acceptance of technologies with perceived radiation hazards.[160] This suggests that effective risk communication, alongside appropriate safety standards, plays an important role in public engagement with nuclear technologies.

Doss has argued that overly conservative radiation protection approaches based on the LNT model may contribute to misconceptions about radiation risks, potentially affecting the adoption of beneficial nuclear applications.[15] While radiation safety remains paramount, continued evaluation of protection standards in light of evolving scientific understanding may help optimize the balance between safety, technological advancement, and societal benefit.

The economic and practical implications of radiation protection standards extend beyond terrestrial applications to critically impact the future of human space exploration. While the implications for manned space travel are beyond the scope of this report, current radiation protection frameworks, if applied directly to space missions, would create insurmountable barriers to long-duration human missions beyond Earth orbit, particularly to Mars and other deep-space destinations.

To advance research and development, operational flexibility through increased occupational limits within the low dose region is needed. However, this does not mean workers will receive higher doses overall or that dose optimization efforts will cease. These changes aim to restore balance at the higher end of the low-dose range, where costs align with the original ALARA philosophy of “reasonable” optimization. Radiation exposure is an accepted occupational risk in the nuclear industry, and this report seeks to reintroduce reasonableness and cost-benefit calculations into dose-management decisions. ALARA originally aimed to ensure that occupational exposures were comparable to risks in other industries while maintaining a net-positive societal benefit. Dose reduction will continue to occur naturally through improved engineering design and control processes to ensure regulatory compliance.

8. DISCUSSION AND POLICY RECOMMENDATIONS

8.1. Scientific Assessment

The comprehensive review of available scientific evidence presented in this report reveals several key conclusions regarding radiation's health effects at dose rates relevant to occupational and public exposures. Epidemiological studies have consistently failed to demonstrate statistically significant health effects at doses below 10,000 mrem delivered at low dose rates. This observation is particularly significant given the decades of research devoted to identifying such effects. Radiobiological evidence further suggests the existence of cellular mechanisms that may reduce or eliminate harmful effects at low doses, including enhanced DNA-repair processes, adaptive responses, and potential hormesis effects. Studies of populations with chronic elevated exposures—particularly those living in areas of high natural background radiation—have not shown conclusive evidence of harm at dose rates comparable to or exceeding occupational limits. Additionally, major professional organizations increasingly acknowledge the limitations of the LNT model at low doses, recognizing the substantial uncertainty in risk estimates below 10,000 mrem.

However, scientific integrity demands acknowledgment of counterarguments to these conclusions. The INWORKS studies have suggested potential risks at doses lower than previously established, though these findings must be considered alongside their methodological limitations. Beyea[161] persuasively argues that radiation protection science represents a complex "jigsaw puzzle" with pieces that do not all fit neatly together, warranting caution when translating scientific debates into practical policy. From an ethical perspective, González[162] proposes that radiation safety has appropriate ethical foundations that transcend purely scientific considerations, suggesting that even when faced with scientific uncertainty, protection standards should err on the side of caution. These counterarguments provide important context for policy development although they do not negate the substantial body of evidence challenging current regulatory approaches.

8.2. Policy Recommendations

Based on our technical assessment of the data, we recommend maintaining an annual occupational dose limit of 5,000 mrem and eliminating all ALARA requirements and limits below this threshold. This approach would maintain the current numerical limit while eliminating the requirement for continuous dose reduction to levels where health effects have not been conclusively demonstrated. We further recommend future consideration of increasing this limit to 10,000 mrem/year. For either limit, an appropriate cumulative-dose constraint should be considered to prevent potential effects from higher lifetime-cumulative exposures. These changes can be easily managed, especially for larger organizations with established programs, through the use of automated access and control systems. Implicit in these recommendations is that typical radiation workers will receive annual exposures well below the limits. Appendix A provides an implementation framework for the proposed regulatory reforms.

While recommending these regulatory changes, we also emphasize the importance of continuing research on low-dose radiation effects to further refine scientific understanding in this area.[163] Additionally, we recommend developing improved risk-communication strategies that more-accurately convey the scientific evidence regarding low-dose radiation risks to both workers and the public. Such communication is essential to address the disproportionate fear of radiation that often drives overly conservative regulatory approaches. For context, it should be noted that nuclear energy is among the safest and cleanest sources of energy generation, comparable in both categories with wind and solar.[164]

9. CONCLUSIONS

Against the backdrop of renewed nuclear-energy prioritization, a critical assessment of factors impeding nuclear-energy deployment becomes essential. This technical review examined radiation protection standards through the lens of contemporary scientific evidence regarding ionizing radiation's health effects and their relationship to the economic and operational challenges facing nuclear-energy expansion.

While acknowledging that the science on low-dose radiation effects remains unsettled, with competing theories and ongoing debate, after comprehensive evaluation of epidemiological data, radiobiological research, and the positions of major scientific organizations, this review—as well as numerous prior studies—finds compelling evidence that current radiation protection standards warrant reconsideration. The balance of available scientific evidence indicates that annual dose rates of 5,000 mrem or less have not been shown to result in detectable increases in adverse health outcomes across diverse human populations and exposure scenarios. Furthermore, substantial evidence suggests that even 10,000 mrem/year may maintain a reasonable safety margin based on available epidemiological and radiobiological data. Current radiation protection frameworks, predicated on the LNT model and implementing ALARA principles below regulatory limits, appear inconsistent with this body of evidence and consequently impose excessive economic and operational burdens without corresponding health benefits.

Given this assessment of the available evidence, we recommend revising radiation–worker-protection standards to maintain an annual occupational-dose limit of 5,000 mrem and eliminating all ALARA requirements and limits below this threshold. This revised approach would maintain protection against demonstrable radiation risks while eliminating requirements for continuous dose reduction in ranges where health effects have not been conclusively demonstrated. We further recommend future consideration of increasing this limit to 10,000 mrem/year with appropriate cumulative-dose constraints. The higher limit of 10,000 mrem/year, while representing a significant shift in regulatory approach, is suggested by multiple lines of scientific evidence from cellular studies, animal research, occupational cohorts, and populations with chronically elevated exposures.

For members of the general public, the current dose limit of 100 mrem per year also appears to be overly restrictive given the lack of observable effects at much-higher levels of natural background radiation experienced by millions of people worldwide. A revised public-dose limit of 500 mrem per year would maintain a substantial safety margin while better aligning with scientific evidence and enabling more cost-effective implementation of beneficial nuclear technologies across energy, healthcare, and industrial sectors.

This recalibrated approach would harmonize longstanding differences in radiation limits between relevant federal agencies and better balance radiation protection with practical and economic considerations while remaining faithful to the weight of scientific evidence and retaining appropriate safety margins for both workers and the public. Importantly, actual occupational exposures in regulated industries typically fall well below regulatory limits, creating an additional practical margin of safety beyond the formal limits. This operational reality provides further assurance that regulatory reform would not result in excessive exposures while allowing substantial economic and operational benefits.

While recognizing the ongoing scientific uncertainties, the recommended changes outlined in this review have the potential to transform the economic landscape for nuclear applications while maintaining appropriate health protections. By reducing unnecessary regulatory burdens, these revisions could dramatically improve the cost-competitiveness and beneficial utilization of nuclear energy, expand access to nuclear-medicine procedures, and enhance industrial applications of nuclear technologies. These changes could also begin to align public perceptions of risks associated with radiation exposure with actual scientific data. These benefits would arrive at a critical moment when nuclear technologies offer essential solutions to pressing societal challenges including climate change, energy security, medical-treatment access, and industrial innovation. Rather than claiming scientific certainty where none exists, aligning radiation protection standards with current scientific understanding represents a prudent step toward realizing these benefits while maintaining appropriate safety margins for workers and the public while acknowledging that some level of scientific uncertainty will likely persist.

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Appendix A

Implementation Framework for Regulatory Reform

This appendix outlines a comprehensive framework to implement the regulatory changes proposed in the main report. The recommendations presented here are designed to translate the scientific findings and policy recommendations into specific, actionable changes to current nuclear-regulatory frameworks. These changes aim to align radiation protection standards with contemporary scientific evidence while maintaining appropriate safety margins and ensuring efficient operation of nuclear technologies across energy, medical, and industrial applications. Note that other dose limits, including organ- and tissue-dose limits, should also be reevaluated, but are beyond the scope of this report.

The proposed modifications target the three primary U.S. regulatory bodies responsible for radiation protection: the Nuclear Regulatory Commission (NRC), the Department of Energy (DOE), and the Environmental Protection Agency (EPA). Each recommendation identifies a specific regulation, its current requirements, and the proposed modifications. This structured approach provides a clear roadmap for regulatory reform that can be implemented through established rulemaking processes.

A-1. NUCLEAR REGULATORY COMMISSION REQUIREMENTS

The NRC's comprehensive radiation protection framework, codified in 10 Code of Federal Regulations (CFR) Part 20, "Standards for Protection Against Radiation," forms the foundation of commercial-nuclear regulation in the United States. The following modifications would align this framework with current scientific understanding while preserving essential safety protections.

A-1.1 10 CFR Part 20—Standards for Protection Against Radiation

A-1.1.1 10 CFR 20.1201—Occupational Dose Limits for Adults

Current Requirement: The regulation establishes an occupational dose limit of 5,000 mrem total effective dose equivalent (TEDE) per year for adult workers.

Recommended Change: We propose first of the following two alternative approaches:

1. **Moderate Reform Approach:** Maintain the current 5,000 mrem annual limit, but eliminate all ALARA requirements and limits below this threshold. This would preserve the existing numerical limit while removing the requirement for continuous dose reduction in ranges where health effects have not been conclusively demonstrated.
2. **Evidence-Based Approach:** Increase the occupational dose limit to 10,000 mrem TEDE per year, with an appropriate 5-year cumulative limit. This approach aligns with scientific evidence showing no detectable health effects below this threshold while still maintaining a significant safety margin.

The second approach would provide greater operational flexibility and economic benefits while maintaining appropriate protection, as detailed in the main report. For either approach, tissue-specific limits should be proportionally adjusted.

A-1.1.2 10 CFR 20.1101—Radiation Protection Programs

Current Requirement: Paragraph (b) requires licensees to "use, to the extent practical, procedures and engineering controls based upon sound radiation protection principles to achieve occupational doses and doses to members of the public that are as low as is reasonably achievable (ALARA)."

Recommended Change: Modify this section to exempt doses below the selected occupational limit (5,000 or 10,000 mrem/year) from all ALARA requirements and limits below the selected threshold. The revised language could state: "Licensees shall use procedures and engineering controls to maintain occupational doses and public doses below the limits specified in this part. For exposures that could reasonably be expected to exceed these limits, licensees shall apply ALARA principles to reduce doses to the extent practicable."

This change would fundamentally shift the regulatory approach from requiring continuous dose reduction at all levels to focusing protection efforts on preventing exposures above scientifically justified limits.

A-1.1.3 10 CFR 20.1301—Dose Limits for Individual Members of the Public

Current Requirement: The regulation limits the TEDE to individual members of the public to 100 mrem per year from licensed operations.

Recommended Change: Increase the public dose limit to 500 mrem TEDE per year. This revised limit would:

- Maintain a significant safety margin below levels where health effects might begin to be detectable
- Remain within the range of natural-background-radiation variations observed globally
- Reduce unnecessary regulatory burden and costs
- Better align radiation protection with risk-informed regulation principles used in other domains.

This five-fold increase from the current limit would still keep public exposures well below levels of health concern while providing significant regulatory relief.

A-1.1.4 10 CFR 20.1302—Compliance with Dose Limits for Individual Members of the Public

Current Requirement: This section establishes methods for demonstrating compliance with the public-dose limit, including survey and measurement requirements.

Recommended Change: Adjust the methodologies to align with the revised 500 mrem public-dose limit. Specifically, the concentration values in Appendix B to Part 20 should be proportionally increased to reflect the higher permissible public dose. Additionally, the compliance-demonstration methods should be streamlined to reduce unnecessary monitoring in situations where doses are unlikely to approach the revised limit.

A-1.1.5 10 CFR 20.2104—Determination of Prior Occupational Dose

Current Requirement: Requires determination of prior occupational radiation dose for certain workers, particularly when they are likely to receive significant exposures.

Recommended Change: If the 10,000 mrem annual limit is adopted, strengthen the requirements for tracking cumulative dose over 5-year periods to ensure compliance with an appropriate cumulative limit. The revised language should specifically require:

- Annual documentation of cumulative dose over the current 5-year monitoring period
- Verification of prior dose history when hiring radiation workers who may have received significant exposures at other facilities
- Clear protocols for cases where workers approach cumulative limit thresholds.

A-1.2 NRC Regulatory Guides

The following NRC guidance documents would require revision to align with the modified regulatory approach.

A-1.2.1 Regulatory Guide 8.8—Information Relevant to Ensuring that Occupational Radiation Exposures at Nuclear Power Stations Will Be ALARA

Current Guidance: Provides detailed guidance on implementing ALARA through facility design features, operational protocols, and administrative controls.

Recommended Change: Revise to encourage ALARA principles only to activities where exposures could reasonably approach or exceed the occupational limit. The guide should be restructured around a graded approach where:

- Activities expected to produce doses well below the limit receive no ALARA consideration
- ALARA planning is encouraged as potential doses increase toward the regulatory limit
- ALARA programs with comprehensive optimization would be expected only for activities with potential to exceed limits.

This approach would focus protection resources where they provide meaningful safety benefits.

A-1.2.2 Regulatory Guide 8.10—Operating Philosophy for Maintaining Occupational Radiation Exposures ALARA

Current Guidance: Establishes ALARA as a fundamental operating philosophy applicable at all dose levels, regardless of their magnitude relative to regulatory limits.

Recommended Change: Revise to explicitly acknowledge that ALARA implementation should be proportional to potential exposure levels. The guide should:

- Eliminate references to dose “minimization” in favor of dose “management”
- Provide criteria for determining when ALARA planning is warranted based on exposure potential
- Offer simplified approaches for routine low-dose activities.

A-1.2.3 Regulatory Guide 8.29—Instruction Concerning Risks from Occupational Radiation Exposure

Current Guidance: Based on the linear no-threshold (LNT) model and presents risk as existing at all dose levels.

Recommended Change: Update to reflect current scientific evidence regarding thresholds for observable health effects. The revised guide should:

- Acknowledge the scientific uncertainty regarding effects below 10,000 mrem
- Present a balanced view of the epidemiological evidence, including studies that have not detected effects at low doses
- Provide context about natural background radiation and its variation
- Eliminate language suggesting that any radiation exposure, no matter how small, carries quantifiable risk.

A-2. DEPARTMENT OF ENERGY REQUIREMENTS

The DOE radiation protection framework, which applies to national laboratories, nuclear-weapons facilities, and environmental-cleanup sites, has historically implemented more-conservative measures than required by regulation. The following changes would align DOE requirements with current scientific understanding.

A-2.1 10 CFR Part 835—Occupational Radiation Protection

A-2.1.1 10 CFR 835.202—Occupational Dose Limits for General Employees

Current Requirement: Establishes an occupational dose limit of 5,000 mrem TEDE per year, matching the NRC limit.

Recommended Change: As with the NRC requirements, we propose the following options:

1. Maintaining the 5,000 mrem limit but eliminating all ALARA requirements and limits below this threshold, or
2. Increasing to 10,000 mrem per year with a 5-year cumulative limit.

For consistency across federal regulations, the approach selected should match the NRC implementation.

A-2.1.2 10 CFR 835.101—Radiation Protection Programs

Current Requirement: Requires comprehensive, formal ALARA programs as part of radiation protection program documentation.

Recommended Change: Modify to exempt doses below the occupational limit from ALARA requirements. The revised language should focus radiation protection programs on:

- Ensuring compliance with dose limits
- Managing higher-risk activities

- Providing appropriate training and monitoring
- Implementing controls proportional to risk.

This approach would eliminate the current practice under which significant resources are devoted to reducing already-low exposures.

A-2.1.3 10 CFR 835.1001—Design and Control

Current Requirement: Establishes ALARA-based design criteria for DOE facilities, focusing on engineered controls to minimize exposure regardless of level.

Recommended Change: Revise to focus design requirements on preventing exposures above the regulatory limit, rather than continuous reduction below the limit. The modified language should:

- Emphasize engineering controls where exposures could exceed limits
- Provide flexibility in design approaches for low-dose areas
- Eliminate requirements for complex engineered solutions when administrative controls can adequately maintain exposures below limits.

A-2.2 DOE Order 458.1—Radiation Protection of the Public and the Environment

Current Requirement: Establishes a public dose limit of 100 mrem/year, consistent with NRC requirements.

Recommended Change: Increase public-dose limit to 500 mrem/year to align with the proposed NRC changes. This would harmonize federal radiation protection standards while maintaining appropriate safety margins for public protection.

A-2.3 DOE Administrative Control Level (ACL)

Current Requirement: Imposes a 2,000 mrem/year DOE-wide ACL, significantly more restrictive than the regulatory limit.

Recommended Change: Eliminate the DOE-wide ACL, allowing facilities to set local administrative controls based on operational considerations rather than arbitrary administrative limits. This change would:

- Provide greater operational flexibility
- Allow risk-informed resource allocation
- Reduce unnecessary administrative burden
- Focus protection efforts where they provide meaningful safety benefits.

A-2.4 DOE Technical Standards and Guidance Documents

A-2.4.1 DOE-STD-1098-2017, Radiological Control

Current Guidance: Implements ACLs and detailed ALARA protocols that often drive operational decisions at DOE facilities.

Recommended Change: Revise to align with the modified regulatory approach, eliminating requirements for continuous dose reduction below regulatory limits. The standard should be restructured to:

- Remove the DOE-wide 2,000 mrem/year ACL
- Provide a graded approach to radiation protection based on potential exposure levels
- Eliminate excessively conservative measures for low-dose activities
- Focus detailed planning requirements on higher-risk operations.

A-2.4.2 DOE G 441.1-1C, Radiation Protection Programs Guide

Current Guidance: Provides detailed guidance on implementing ALARA through formal program elements.

Recommended Change: Update to reflect the revised approach that exempts exposures below regulatory limits from ALARA requirements. The revised guide should:

- Focus on compliance with limits rather than continuous reduction
- Maintain that prudent radiological practices continue to be an expectation
- Eliminate guidance suggesting that all radiation exposure must be justified regardless of level.

A-3. ENVIRONMENTAL PROTECTION AGENCY REQUIREMENTS

The EPA's radiation protection standards are particularly fragmented, with multiple media-specific and facility-specific requirements that create a complex regulatory landscape. Harmonizing these standards with the scientific evidence and the proposed NRC and DOE changes would provide significant regulatory relief.

A-3.1 40 CFR Part 190—Environmental Radiation Protection Standards for Nuclear Power Operations

A-3.1.1 40 CFR 190.10—Standards for Normal Operations

Current Requirement: Limits radiation doses to the public from nuclear fuel-cycle facilities to 25 mrem/year to the whole body, 75 mrem/year to the thyroid, and 25 mrem/year to any other organ.

Recommended Change: Harmonize with the revised public dose limit of 500 mrem/year. The revised standard should:

- Adopt the TEDE methodology used by NRC and DOE rather than separate organ-specific limits
- Set a single consistent limit aligned with the 500 mrem/year public-dose standard
- Eliminate unnecessary conservatism in compliance assessment methods.

A-3.2 40 CFR Part 61—National Emission Standards for Hazardous Air Pollutants

A-3.2.1 40 CFR 61.92—Standard (Subpart H—National Emission Standards for Emissions of Radionuclides)

Current Requirement: Limits emissions to levels that would cause no member of the public to receive an effective dose equivalent exceeding 10 mrem/year.

Recommended Change: Increase to align with the revised public dose framework, potentially to 50 mrem/year. This five-fold increase would maintain the same proportional relationship to the overall public-dose limit while providing significant regulatory relief for facilities with airborne emissions.

A-3.3 40 CFR Part 141—National Primary Drinking Water Regulations

A-3.3.1 40 CFR 141.66—Maximum Contaminant Levels for Radionuclides

Current Requirement: Limits beta particle and photon radioactivity from man-made radionuclides in drinking water to 4 mrem/year to the total body or any organ.

Recommended Change: Increase proportionally with the revised public dose limit, potentially to 20 mrem/year. This change would:

- Maintain the same relative contribution to total public exposure
- Reduce unnecessary treatment costs
- Align better with natural-background variations
- Focus resources on more-significant public health concerns.

A-4. IMPLEMENTATION STRATEGY

The implementation of these regulatory changes can follow both traditional regulatory pathways and more-innovative approaches designed to accelerate reform. This dual-track strategy recognizes the importance of thorough process while acknowledging the significant economic and operational benefits that could be realized through faster implementation. The comprehensive approach outlined below combines established regulatory mechanisms with innovative strategies to achieve meaningful reform in both the near and long term.

A-4.1 Traditional Regulatory Pathways

A-4.1.1 Rulemaking Process

The conventional approach to regulatory reform begins with a carefully structured rulemaking process. This would commence with the formation of an interagency working group composed of senior representatives from the NRC, DOE, and EPA. This collaborative body would be charged with establishing a unified scientific foundation, developing a coordinated implementation timeline, and ensuring regulatory consistency across agencies. The working group's first priority should be developing shared scientific positions and addressing potential jurisdictional overlaps that might otherwise lead to conflicting requirements.

With interagency alignment established, the reform effort would then move to comprehensive public engagement. This would begin with issuing Advance Notices of Proposed Rulemaking to formally signal the contemplated changes and solicit initial feedback. Concurrently, agencies would conduct regional

public workshops designed to explain the scientific basis for reform, illustrate potential economic benefits, and address concerns from various perspectives. Special attention would be paid to engaging key stakeholder groups including nuclear facility operators, medical institutions, radiation protection professionals, labor organizations, and environmental advocates. These early consultations would help identify implementation challenges and refine the regulatory approach before formal proposals are developed.

The formal rulemaking phase would then proceed through coordinated Notices of Proposed Rulemaking issued by each agency. These notices would present draft regulatory language developed based on the interagency scientific position and informed by stakeholder feedback. Formal public-comment periods would follow, supplemented by public hearings in regions with significant nuclear activities. Agency staff would then undertake a thorough and transparent review of all comments received, documenting responses and resulting modifications to the proposed rules. The process would culminate in the publication of final rules with carefully phased implementation timelines that acknowledge the operational adjustments required of regulated entities.

Technical-Basis Documentation

Robust technical documentation forms the essential foundation of defensible regulatory reform. The interagency working group would oversee development of comprehensive technical-basis documents that thoroughly analyze the epidemiological and radiobiological evidence supporting the new dose limits and regulatory approach. These documents would present a balanced assessment of the scientific literature, explicitly addressing areas of uncertainty and alternative viewpoints with intellectual rigor rather than selectively citing supportive studies. This transparent approach acknowledges the complexity of radiation science while building confidence in the regulatory conclusions.

With the scientific foundation established, agencies would then undertake a systematic review and revision of all associated regulatory guidance documents. Updated guides would provide clear implementation pathways aligned with the new requirements, featuring practical examples and detailed case studies that illustrate compliant approaches across different operational scenarios. Specialized training materials would be developed for both regulators and licensees to ensure consistent understanding of the revised requirements and their practical application.

The technical framework would be completed with the development of specific compliance demonstration methods. This includes updating calculation methodologies, revising radiation protection software tools, and creating standardized templates for program documentation. These practical resources would enable regulated entities to efficiently implement the revised requirements while maintaining consistent compliance approaches across the industry.

Transition Mechanisms

Recognizing that regulatory transformation cannot occur overnight, the traditional implementation strategy incorporates a carefully designed transition period. This begins with establishing reasonable timeframes for facilities to adapt their radiation protection programs to the new requirements. The transition schedule would reflect the complexity of needed changes, with more time allocated for modifications requiring significant operational or infrastructure adjustments. Throughout this period, regulators would permit gradual adaptation to new requirements while maintaining focus on overall radiation-safety objectives.

The transition would be supported by a modified enforcement approach designed to facilitate adaptation rather than penalize noncompliance during the adjustment period. Regulatory agencies would develop interim enforcement-discretion policies that emphasize programmatic progress rather than isolated compliance issues. Inspection activities would focus on education and assistance, with enforcement actions reserved for situations presenting significant safety concerns rather than technical nonconformances with new requirements.

To facilitate efficient implementation, agencies would develop comprehensive resource packages for regulated entities. These would include implementation guides, assessment tools, and program templates tailored to different facility types and operational scenarios. Technical assistance would be readily available through dedicated help desks, while a series of implementation workshops and webinars would provide opportunities for direct engagement with regulatory staff and peer facilities undergoing similar transitions.

Innovative Acceleration Strategies

While traditional regulatory processes provide thoroughness and procedural rigor, they typically require multiple years for full implementation. The following innovative approaches could significantly accelerate the realization of benefits from the proposed reforms, often without requiring the completion of full rulemaking processes.

Executive and Secretarial Directives

Agency leadership can drive immediate change through executive actions while formal regulatory revisions proceed.

The NRC chairman could issue a policy directive instructing staff to exercise enforcement discretion for ALARA requirements at exposures below the 5,000 mrem threshold. This directive would immediately shift inspection focus away from low-dose ALARA compliance without requiring rule changes.

Similarly, the Secretary of Energy could issue a departmental order allowing facilities to utilize the full regulatory limit of 5,000 mrem without additional justification or approvals.

The EPA administrator could also take immediate executive action by issuing a policy memorandum directing enforcement discretion for radiation standards. This could include instructing regional offices to prioritize enforcement only for exposures approaching or exceeding the 100 mrem annual public-dose limit rather than the more restrictive media-specific standards (such as the 10 mrem annual air-pathway limit or 4 mrem annual drinking-water limit). Additionally, the administrator could issue interpretive guidance clarifying that compliance with the overall 100 mrem public-dose standard automatically demonstrates compliance with individual-pathway standards, effectively streamlining the complex web of EPA radiation requirements without requiring immediate rule changes.

These leadership directives would provide immediate operational flexibility while formal rulemaking proceeds in parallel. By using existing administrative authorities, agency heads can significantly reduce regulatory burden and begin delivering economic benefits years before the completion of formal rule revisions.

Regulatory Sandboxes and Pilot Programs

Testing regulatory innovations in controlled environments can accelerate broader implementation.

Regulatory agencies could establish “sandbox” programs where selected facilities implement the proposed framework under special exemptions or authorizations. For example, the NRC could authorize several nuclear power plants to operate under a 10,000 mrem annual limit with simplified radiation protection programs exempt from ALARA requirements below this threshold. These facilities would implement enhanced monitoring and reporting to document outcomes, safety performance, and economic benefits. DOE could similarly designate certain national laboratories or production facilities as pilot sites implementing the revised approach. The documented success of these programs would build evidence and momentum for broader implementation while providing real-world validation of the proposed approach.

A-4.1.2 Risk-Informed Enforcement Policy

Immediate shifts in enforcement priorities can deliver many benefits before rules change. Regulatory agencies could announce comprehensive revisions to their enforcement policies, explicitly directing inspection resources toward practices with a potential to exceed regulatory limits while deemphasizing or eliminating enforcement of ALARA-related findings at lower dose levels. For example, the NRC could issue an enforcement guidance memorandum stating that ALARA violations will not be cited unless doses exceed 50% of regulatory limits or specific high-risk conditions exist. This approach would deliver many benefits of the proposed regulatory changes through enforcement discretion rather than waiting for rule changes.

A-4.1.3 Performance-Based Alternative Compliance Pathways

Creating alternative compliance options can enable innovation under existing rules. Agencies could establish performance-based alternative compliance pathways that allow facilities to demonstrate equivalent safety outcomes through means different from current prescriptive requirements. For example, the NRC could issue a regulatory-issue summary establishing an alternative compliance approach where licensees could replace detailed ALARA programs with simplified safety-management systems focused on maintaining exposures below appropriate thresholds. The DOE could similarly approve alternative radiation protection program structures under existing regulatory authority. This approach would enable innovation while maintaining compliance with existing regulations.

A-4.1.4 Comprehensive Legislative Reform

Legislative action could mandate coordinated reform and establish implementation deadlines. Rather than pursuing agency-by-agency regulatory changes, congressional action could establish a unified framework through legislation. Such legislation would direct all relevant federal agencies to implement the revised radiation protection framework with specific deadlines and requirements. This approach would bypass much of the procedural complexity of coordinating multiple agency rulemakings and could establish a uniform framework that eliminates current inconsistencies between agencies. The legislation could specifically mandate elimination of ALARA requirements below regulatory limits and potentially increase occupational limits to 10,000 mrem annually while establishing implementation requirements and deadlines for all affected agencies.

A-4.1.5 Negotiated Rulemaking

Collaborative rule development can expedite implementation and reduce legal challenges. Rather than traditional notice-and-comment rulemaking, agencies could establish negotiated rulemaking committees with balanced representation from industry, professional organizations, environmental groups, and regulatory agencies. These committees would be charged with developing consensus-based regulatory language that balances safety, operational flexibility, and economic considerations. This collaborative approach typically produces more-implementable rules with broader stakeholder support, reducing subsequent legal challenges and implementation resistance. The negotiated rulemaking process can often be completed more quickly than traditional rulemaking while producing more-pragmatic and balanced regulatory language.

A-4.1.6 Immediate Guidance Revision

Updating guidance documents can provide significant relief while rules are being changed. While formal regulations may require years to modify, regulatory-guidance documents can often be revised much more quickly and with fewer procedural requirements. Agencies could immediately update key guidance documents to clarify that ALARA implementation should be proportional to potential exposure levels, with minimal requirements for activities unlikely to approach regulatory limits. For example, the

NRC could revise Regulatory Guide 8.10 to establish a graded approach to ALARA based on potential exposure levels, significantly reducing requirements for lower-dose activities. This revised guidance would provide substantial operational relief even while formal regulations remain unchanged.

A-4.1.7 Digital Compliance Systems

Technology-enabled approaches can streamline implementation. The transition to revised regulatory frameworks could be accelerated by developing digital compliance systems that automatically evaluate radiation protection measures based on potential exposure levels. These systems would integrate radiation-monitoring data, work-planning information, and regulatory requirements to generate risk-informed protective measures without unnecessary conservatism. Federal agencies could sponsor development of open-source compliance platforms or approve commercial systems that implement the revised approach. When paired with the regulatory changes, these digital systems would dramatically reduce administrative burden while maintaining safety and ensuring consistent implementation.

A-4.1.8 Federal-State Implementation Agreements

Coordinated approaches with agreement states can ensure nationwide consistency. For NRC regulations, the development of model-implementation agreements with agreement states—that is, states with delegated regulatory authority over certain nuclear materials—would ensure consistent application of the revised framework nationwide. These agreements would prevent a patchwork of different requirements across states and accelerate implementation by providing clear guidance to state regulators. The NRC could conduct focused workshops with agreement-state representatives to develop consensus implementation approaches that deliver the benefits of regulatory reform while respecting state authority and perspectives.

A-4.2 Monitoring and Evaluation

Regardless of the implementation pathway selected, robust monitoring and evaluation mechanisms are essential to assess effectiveness and identify needed adjustments. Health surveillance would be enhanced for workers with exposures in the 5,000–10,000 mrem range to provide additional data on potential health effects in this dose band. This would complement ongoing epidemiological studies of radiation workers, with specific protocols developed to evaluate whether the revised framework maintains appropriate health protection. Standardized data-collection systems would be established to enable consistent evaluation across different agencies and facility types.

The implementation would be subject to formal review after 5–10 years to evaluate its effectiveness and identify potential improvements. This review would examine health-surveillance data, assess economic impacts compared to projections, and compile operational experience from regulated entities. The findings would inform potential adjustments to the framework based on implementation lessons and any emerging scientific insights developed during the intervening period.

Finally, the reformed U.S. approach would be positioned within the international radiation protection community through active engagement with organizations like the International Commission on Radiological Protection and the International Atomic Energy Agency. U.S. representatives would share implementation experiences and health-surveillance data with the international community while participating in global efforts to refine radiation protection approaches. This international dialogue would ensure that U.S. practices remain informed by global developments while also allowing American experience to influence international radiation protection evolution.

A-4.3 Recommended Implementation Approach

Based on the options outlined above, we recommend a hybrid implementation strategy that combines elements of both traditional and innovative approaches to maximize both effectiveness and speed. Specifically:

1. Initiate traditional rulemaking processes for comprehensive regulatory reform while simultaneously implementing immediate enforcement-discretion policies that redefines ALARA requirements in the low-dose region and when below regulatory limits
2. Establish pilot programs at selected facilities to implement the 10,000 mrem occupational limit approach, generating real-world data on safety outcomes and economic benefits while broader regulatory changes proceed
3. Update regulatory guidance documents immediately to reflect a graded approach to radiation protection based on potential exposure levels, providing significant operational relief without waiting for rule changes
4. Develop model implementation agreements with agreement states to ensure consistent nationwide application of the revised approach
5. Establish robust monitoring and evaluation mechanisms to assess the effectiveness of both interim measures and permanent regulatory changes.

This hybrid approach would deliver significant near-term benefits through executive actions and guidance revisions while establishing a solid foundation for comprehensive regulatory reform through traditional rulemaking processes. The early implementation of key elements would generate valuable experience to inform and potentially accelerate the broader regulatory changes.

A-5. CONCLUSION

The regulatory changes outlined in this appendix would significantly reform the radiation protection framework in the United States to better align with current scientific evidence while maintaining appropriate safety margins. By focusing protection efforts where they provide meaningful safety benefits, these changes would reduce unnecessary economic and operational burdens without compromising worker and public health.

The implementation approach provides a clear roadmap for transitioning to a more scientifically sound regulatory system that balances protection with practical considerations. This balanced approach would enable more-efficient deployment of nuclear technologies for energy, medical, and industrial applications while continuing to protect workers and the public from demonstrated radiation risks.

This reform represents a significant opportunity to enhance the economic competitiveness of nuclear technologies while maintaining America's world-leading safety record. By focusing regulatory attention on meaningful risks and eliminating unnecessary burden when science indicates minimal concern, these changes would help realize the full potential of nuclear technology in addressing our nation's energy, healthcare, and industrial needs.

Appendix B

Consideration of Higher Dose Limits

B-1. Evidence Supporting a 10,000 mrem/year Limit

Multiple lines of evidence support consideration of a 10,000 mrem/year occupational dose limit. Epidemiological studies across various exposure scenarios show limited or no statistically significant health effects below this threshold. The Health Physics Society explicitly states that "below 10,000 mrem (including occupational and environmental exposures), risks of health effects are either too small to be observed or are nonexistent." This professional assessment reflects the consensus of radiation protection experts evaluating the totality of available evidence.

Studies from regions with elevated natural background radiation provide particularly compelling real-world evidence. Populations in parts of Kerala, India, experience lifetime exposures up to 7,000 mrem/year while residents of Ramsar, Iran, live with even higher background levels. Despite these elevated chronic exposures, researchers have not demonstrated conclusive evidence of increased cancer rates or other adverse health effects in these populations. This natural experiment spanning generations seems to provide strong evidence against significant health risks at these exposure levels; however, as the report noted in Section 3.2.3, this outlook is tempered through other findings that caution against over-interpreting findings in the high-natural-background region.

Professional organizations broadly acknowledge the limitations of epidemiological studies at lower doses. Both NCRP Commentary No. 27 and the BEIR VII report state that at doses less than 10,000 mrem "statistical limitations make it difficult to evaluate cancer risk in humans." This recognition of the practical limits of epidemiological detection capabilities suggests that if risks exist at these levels, they are too small to be reliably measured against background cancer rates.

The standard application of radiation-risk models likely overestimates risks from chronic occupational exposures. Epidemiological data from atomic-bomb survivors reflects acute-exposure scenarios that are fundamentally different from workplace exposures. A DREF of 1.5–2 is recommended when extrapolating from acute to chronic exposures, suggesting that risks at low dose rates may be half or less those observed in atomic-bomb survivors.

Radiobiological evidence further supports the consideration of higher limits. Cellular-repair mechanisms demonstrate significantly higher efficiency at low dose rates, and substantial evidence exists for adaptive responses and potential hormesis effects that might further reduce risks at chronic low-to-moderate exposures. These biological mechanisms suggest that the simple linear extrapolation of risks from high to low doses may substantially overestimate actual biological effects. Even though cellular responses at low doses tend to vary greatly, depending upon the end point of interest, ultimately, regardless of the response, the projected risk remains low.

B-1.1 Safety-Margin Considerations

A 10,000 mrem/year limit would incorporate several layers of safety even while allowing greater operational flexibility. Because deleterious health effects have not been conclusively demonstrated below this level, setting the limit at 10,000 mrem/year already builds in a statistical-uncertainty buffer. This approach acknowledges that even if effects exist at this level, they are too small to be reliably detected against background cancer rates. It should be noted that nuclear energy is among the safest and cleanest sources of energy generation, comparable in both categories with wind and solar.[o]

Implementing a cumulative exposure limit would prevent continuous high-end exposures and further reduce potential risks from lifetime accumulation. This tiered approach provides protection against the possibility that effects might emerge from long-term cumulative exposure even if annual exposures remain below detection thresholds.

Though the evidence suggests possible thresholds or non-linear responses below 10,000 mrem/year, using this limit would still acknowledge the possibility of some risk, albeit potentially too small to detect. This approach maintains a precautionary element while allowing more operational flexibility than current frameworks.

Additionally, actual occupational exposures typically fall well below regulatory limits in practice, creating an additional practical margin of safety. Experience in regulated industries demonstrates that most workers receive only a fraction of allowable doses, with only specialized roles approaching regulatory limits. This operational reality provides further assurance that raising the regulatory limit would not result in widespread high exposures.

B-1.2 Implementation Considerations

If a revised annual occupational dose limit of 10,000 mrem/year were adopted, implementation could include elements to ensure continued protection while reducing unnecessary regulatory burden. A cumulative 5-year dose limit would prevent continuous maximum exposures and provide protection against potential effects of lifetime dose accumulation. The elimination of ALARA requirements below the 10,000 mrem threshold would reduce the economic and operational burden of continuous dose reduction below levels where health effects have not been conclusively demonstrated.

Continued monitoring and epidemiological studies of workers with exposures in the 5,000–10,000 mrem/year range would further refine understanding of health effects in this dose range and provide ongoing validation of the regulatory approach. Enhanced medical surveillance for workers who approach the cumulative limits would provide additional protection and data-collection opportunities.

While some evidence suggests that even-higher dose limits might be acceptable based strictly on health-effects data, a 10,000 mrem/year limit represents a reasonable balance between scientific evidence and prudent safety margins in radiation protection. This approach acknowledges remaining uncertainties while avoiding excessive conservatism that imposes significant economic costs without demonstrable health benefits.

This report has cited numerous studies and publications documenting the generally defined low dose region where current regulatory limits have been established. However, there is no definitive basis that demonstrates why the current limits constitute the "correct values" for occupational dose limits. This report addresses this low-dose region and notes that over a long period of time, dose limits have continuously been reduced based on a theory that all radiation responses equate to deleterious statistical health effects. This report recognizes that there is a biological response to radiation; however, that does

[o] Ritchie, H. 2020. "What are the safest and cleanest sources of energy?" Published online at OurWorldinData.org. Retrieved from: https://ourworldindata.org/safest-sources-of-energy.

not automatically equate to increased risk such that all doses should be maintained as close to zero as possible. Rather, we can and have successfully managed these risks, and through that management we have improved the health and lives of millions through the responsible use of radiation.

B-2. Implications for Public Dose Limits

The current public dose limit of 100 mrem per year similarly warrants reconsideration based on the scientific evidence reviewed in this report. This limit appears unnecessarily restrictive based on several key observations. Many populated areas worldwide have natural background radiation levels exceeding 300–500 mrem/year, with some inhabited regions exceeding 1,000 mrem/year, all without demonstrable adverse health effects. This natural variation suggests that the current 100 mrem/year limit provides no discernible health benefit relative to natural background exposures experienced by millions of people globally.

The economic costs of maintaining public exposures below 100 mrem/year have not been quantified in the literature but are known to be substantial. Nuclear facilities often require complex and expensive engineering controls to maintain public doses at a small fraction of natural background radiation levels, with no demonstrable public-health benefit. These costs ultimately affect energy prices, healthcare costs, and industrial competitiveness.

From a comparative risk perspective, the estimated lifetime cancer risk from exposure at the current limit (100 mrem/year) is approximately 0.005% according to LNT-model calculations. This hypothetical risk is orders-of-magnitude lower than many commonly accepted voluntary risks and far smaller than variations in cancer risk due to geographic location, lifestyle factors, or socioeconomic status. This disproportionate focus on extremely small theoretical radiation risks diverts attention and resources from more-significant public-health concerns.

Given that epidemiological studies have consistently failed to demonstrate statistically significant health effects at doses below 10,000 mrem, a public limit of 100 mrem/year represents an excessive safety factor of 100 times. Such extreme conservatism goes well beyond prudent precaution into the realm of regulatory burden without corresponding benefit.

The EPA's multilayered approach with various pathway-specific and source-specific limits (often in the 10–25 mrem/year range) creates an even more-restrictive regulatory environment that compounds the economic burden without scientific justification. These standards effectively require dose constraints that are 200–500 times below levels where health effects might begin to be detectable, an approach not applied to other environmental or public-health hazards.

Based on these considerations, we recommend that public-dose limits could reasonably be revised upward to 500 mrem/year. This revised limit would still maintain a 10–20-fold safety factor below levels where effects might begin to be detectable, remain within the range of natural background variations observed globally, reduce unnecessary regulatory burden and costs, and better align radiation protection with the principles of risk-informed regulation used in other domains.

Additionally, the EPA's multiple pathway-specific and source-specific standards should be harmonized and simplified into a coherent framework based on the 500 mrem/year public dose limit, with appropriate flexibility for specific exposure pathways. This would eliminate the current fragmented approach under which different media (air, water, soil) and different facilities are regulated under inconsistent standards with varying levels of conservatism.

Such a revision would maintain appropriate protections for members of the public while enabling more cost-effective deployment of nuclear technologies for energy, medical, and industrial applications that provide substantial benefits to society. This balanced approach would better align radiation protection with our scientific understanding while maintaining appropriate safety margins for public protection.