COMPETITIVE ENTERPRISE INSTITUTE
40TH ANNIVERSARY

Myths and Facts in Radiation Risks

A simple solution to remove obstacles to nuclear power

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April 2024

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Introduction

Nuclear power is probably the only known energy source that can support the world's growing energy needs while simultaneously reducing global carbon dioxide emissions.[1] Nuclear power has among the lowest carbon emissions per unit of energy produced of any energy source, and it is one of the most energy-dense and reliable sources of energy, with a small land footprint relative to other carbon-free energy sources.[2] Nuclear power has long been one of the safest energy sources as well, and the technology continues to improve.[3]

Small modular reactors promise to make nuclear safer, and should also be cheaper, simpler, and faster to build than traditional light-water reactors.[4] Breeder reactors generate more fuel than they consume.[5] Reprocessing capabilities allow recycling of materials from spent nuclear fuel, thereby reducing nuclear waste.[6] And molten salt reactors reduce the likelihood of a catastrophic meltdown scenario.[7] Nuclear also forms a reliable backup source for renewables like wind and solar, which suffer from intermittency issues.

Yet, despite the growing need for nuclear power, and despite the many innovations in nuclear technology in recent decades, nuclear provided just 10 percent of the world's electricity and 4 percent of global energy consumption in recent years.[8] In the United States, about 18 percent of electricity generation comes from nuclear, compared to 60 percent from fossil fuels and 21 percent from renewables.[9] Public policy obstacles are certainly a major obstacle preventing nuclear from contributing more to US energy production. Safety regulations significantly increase the cost of nuclear power plant construction and are a contributing factor for why nuclear projects often experience cost overruns.[10]

One issue in the United States is a lack of new nuclear plant designs licensed since the creation of the Nuclear Regulatory Commission (NRC).[11] Another problem facing nuclear is the long history of fear surrounding nuclear technology since the invention of the atomic bomb and the well-known meltdowns or partial meltdowns at sites like Chernobyl in the Soviet Union, Three Mile Island in the US, and more recently in Fukushima, Japan.

While high doses of radiation are certainly dangerous, fears of radiation are largely unfounded when it comes to low-dose exposure.[12] That has not stopped fears from proliferating in popular culture. Who can forget the three-eyed fish swimming near Homer's nuclear power plant on the show "The Simpsons"? In more recent years, HBO's hit show "Chernobyl" and the Netflix miniseries "Three Mile Island" have continued to perpetuate longstanding myths surrounding the danger of nuclear power.[13]

The reality however is that "radiation-induced genetic effects in the offspring of irradiated parents have never been observed in humans."[14] Even so, strict regulations and overly-conservative safety standards

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1 Michael Shellenberger, "Biden Goes Nuclear in Big Atomic Humanist Victory," Public, May 7, 2021, https://public.substack.com/p/biden-goes-nuclear-in-big-atomic.

2 "3 Reasons Why Nuclear Is Clean and Sustainable," Department of Energy, accessed November 14, 2023, https://www.energy.gov/ne/articles/3-reasons-why-nuclear-clean-and-sustainable.

3 James Conca, "How Deadly is Your Kilowatt? We Rank the Killer Energy Sources," Forbes, June 10, 2012, http://www.forbes.com/sites/jamesconca/2012/06/10/energys-deathprint-a-price-always-paid/2/.

4 "What Are Small Modular Reactors (SMRs)?" International Atomic Energy Agency, accessed November 14, 2023, https://www.iaea.org/newscenter/news/what-are-small-modular-reactors-smrs.

5 Sharryn Dotson, "The History and Future of Breeder Reactors," Power Engineering, June 25, 2014, https://www.power-eng.com/nuclear/reactors/the-history-and-future-of-breeder-reactors/#gref.

6 "Reprocessing," Nuclear Regulatory Commission, accessed December 1, 2023, https://www.nrc.gov/materials/reprocessing.html.

7 "Molten Salt Reactors (MSR)," International Atomic Energy Agency, accessed November 14, 2023, https://www.iaea.org/topics/molten-salt-reactors.

8 Hannah Ritchie, Pablo Rosado, and Max Roser, "Nuclear Energy," Our World in Data, June 10, 2020, https://ourworldindata.org/nuclear-energy.

9 "Frequently Asked Questions: What is U.S. electricity generation by source?" US Energy Information Administration, accessed December 12, 2023, https://www.eia.gov/tools/faqs/faq.php?id=427&t=3.

10 Nancy W. Stauffer, "Building Nuclear Power Plants: Why Do Costs Exceed Projections?" MIT Energy Initiative, November 25, 2020, https://energy.mit.edu/news/building-nuclear-power-plants/.

11 Matthew Glavish, "America's Misguided Nuclear Policy Threatens Tech Advantage, Climate Goals," American Enterprise Institute, February 4, 2022, https://www.aei.org/technology-and-innovation/americas-misguided-nuclear-policy-threatens-tech-advantage-climate-goals/.

12 Antone L. Brooks, James Conca, Wayne M. Glines, and Alan E. Waltar. "How the Science of Radiation Biology Can Help Reduce the Crippling Fear of Low-level Radiation," *Health Physics*, Vol. 124, No. 5 (2023), pp. 407-424, https://doi.org/10.1097/HP.0000000000001677.

13 Brittney Bender, "Three Mile Island Netflix Docuseries: A Nuclear Engineer Responds," Bleeding Cool, May 15, 2022, https://bleedingcool.com/tv/three-mile-island-netflix-docuseries-a-nuclear-engineer-responds/.

14 John J. Cardarelli II and Brant A. Ulsh, "It Is Time to Move Beyond the Linear No-Threshold Theory for Low-Dose Radiation Protection," *Dose-Response*, Vol. 16, No. 3 (2018), pp. 1-24, https://doi.org/10.1177/1559325818779651.

make it difficult and expensive to build nuclear power plants.[15] Over time, fears of radiation have become baked into scientific practices that guide regulatory standards, contributing to a climate of "radiophobia."[16] Government risk assessments use default assumptions that assume any amount of radiation exposure, no matter how small, heightens the risk of cancer. This assumption comes under the unassuming name of the "linear no-threshold" (LNT) dose response assumption in radiation risk assessment.

This paper explores how fixing radiation risk assessments can give a boost to an important source of electricity generation, reducing regulatory costs and alleviating unfounded fears of radiation in the process. The paper begins by exploring the basics of risk assessment before turning to the specifics of the LNT assumption. Due to the significant uncertainty surrounding human health effects from exposure to radiation, the assumption of a linear relationship between exposure and risk has historically been a policy choice rather than a scientific one, as acknowledged by leading US regulatory agencies.

The paper goes on to explain how the NRC uses LNT in setting regulatory standards, and how its approach is guided by a form of the precautionary principle, which recommends that hazards be regulated irrespective of whether it can be scientifically demonstrated that they pose risk. The NRC revisited the LNT assumption in recent years, deciding ultimately to uphold it. In making this decision, the agency relied on outdated science and studies, ignored or did not review scientific evidence contrary to the LNT policy, and accepted at face value comments from agencies and scientific bodies that may have had biases or conflicts of interest.

The paper concludes that objective risk assessment requires a separation of policy from science. That is, admittedly, not always easy to accomplish because of uncertainty. Fortunately, scientific knowledge and understanding of repair mechanisms and beneficial health effects from low level radiation exposure has now likely advanced to a point where agencies like the NRC can revisit default policy judgements like the LNT.

The basics of risk assessment

Risk assessment is a process for evaluating the risks associated with human health hazards. It involves identifying a hazardous agent and at-risk populations, the likely levels of exposure experienced by the population, and the consequences of exposure.[17] Risk *assessment* is sometimes distinguished from risk *management*. The former, involving the estimation of risks, is considered an objective science, while the latter is focused on what to do about risks once they are understood,[18] which is something science cannot answer.[19]

The 1983 National Research Council book, *Risk Assessment in the Federal Government: Managing the Process*,[20] delineates between risk assessment and risk management in this way, and it is considered a foundational document in the field of risk assessment. The book describes risk assessment as it pertains to public health as a four-step process, where the steps include:

- Hazard identification: This step involves identifying dangerous agents or activities. In the case of radiation, the potential hazards might include large emissions stemming from meltdowns or other accidents, as well as low-level emissions that accrue over time to workers and populations in areas surrounding nuclear plants.

[15] Sam Batkins, Philip Rossetti and Dan Goldbeck, "Putting Nuclear Regulatory Costs in Context," American Action Forum, July 12, 2017, https://www.americanactionforum.org/research/putting-nuclear-regulatory-costs-context/.

[16] Jodi Strzelczyk, William Edward Potter, and Zygmunt Zdrojewicz, "RAD-BY-RAD (BIT-BY-BIT): Triumph of Evidence over Activities Fostering Fear of Radiogenic Cancers at Low Doses," *Dose-Response*, Vol. 5, No. 4 (2007), pp. 275-283, https://doi.org/10.2203/dose-response.07-021.Strzelczyk.

[17] Kenneth L. Mossman, "The LNT Debate in Radiation Protection: Science vs. Policy." *Dose-Response,* Vol. 10, no. 2 (2012), pp. 190–202, https://doi.org/10.2203/dose-response.11-017.Mossman.

[18] Included in risk management are benefit-cost analysis, enforcement policies at agencies, personal beliefs and preferences, political factors, considerations raised from comments on proposed rules and other policies, and law itself, including establishment of precedent and *de minimis* considerations.

[19] David Hume's "is-ought" principle makes a fundamental distinction between descriptive statements (what "is") and prescriptive or normative statements (what "ought" to be). Normative conclusions (how things should be) cannot be logically derived from purely descriptive premises (how things are).

[20] National Research Council, Committee on the Institutional Means for Assessment of Risks to Public Health, *Risk Assessment in the Federal Government: Managing the Process* (Washington DC: National Academies Press, 1983), https://doi.org/10.17226/366.

- Dose-response assessment: This step involves determining the relationship between a measure of the hazardous agent and the likelihood and severity of the associated health effects. In the case of radiation exposure, this involves determining the risk of cancer or other health effects experienced at different levels and rates of exposure.
- Exposure assessment: This step involves determining the extent to which various populations are in contact with the hazardous agent. In the case of a nuclear power plant, this might involve assessing the potential levels of exposure to workers and the general public by measuring radiation levels in and around a plant.
- Risk characterization: This final step involves combining the information from the previous steps to estimate the overall risk associated with the hazardous agent. This means calculating the probability and severity of different health endpoint cases arising based on different levels of exposure in a population. A risk estimate should be a probability-weighted prediction of health outcomes, such as the expected number of cancer cases or instances of premature mortality across a population.

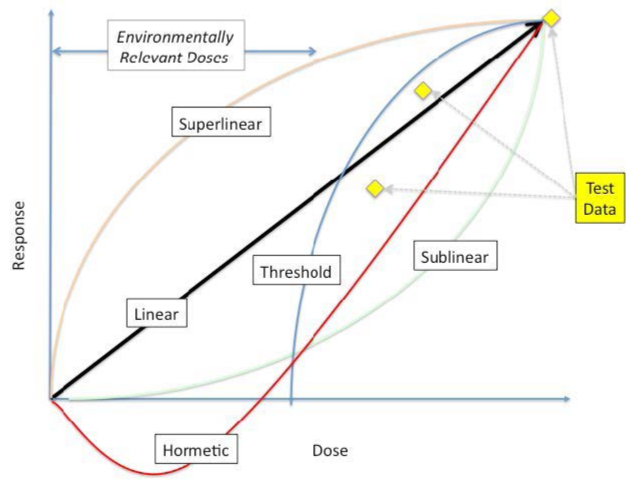
Figure 1 provides examples of several dose-response models, one of which is the LNT. A dose-response model is typically used to fit test data that are available at relatively high doses but for which limited evidence is available at the low doses most human beings experience in their day-to-day environments.[21] Test data tend to come from animal studies, human studies of exposure to occupational hazards, or from epidemiological studies.

LNT replaced a long-held "tolerance dose" or "permissible dose" concept in 1956, based on questionable reasoning from a National Academy of Sciences panel.[22] Eventually, LNT came to be the default dose-response model for carcinogens, but the history as to how this came to be is full of controversy, as this paper will explore a little later on.[23]

Other models besides LNT are also widely in use. For example, a threshold model assumes that below some exposure level a hazard poses risks indistinguishable from background exposures. The threshold model remains the default for most non-carcinogenic substances. There is also a sublinear dose-response model, where low doses of the hazard are minimally harmful, but risk rises in an exponential fashion at higher levels of exposure. With a sigmoidal, or S-shaped, dose-response function (not pictured), risks also start off as modest before rising exponentially, but there is some level of exposure where risks start to flatline.

Finally, with a hormetic, or J-shaped, dose-response, low doses of exposure actually reduce risks, generally by activating repair mechanisms in cells, which result in beneficial health effects. An example of hormesis is the selective removal of pre-cancerous cells from cell populations that are exposed to low doses of radiation.[24]

Figure 1: Examples of Dose-Response Models



Source: Richard Belzer, "Risk Assessment, Safety Assessment, and the Estimation of Regulatory Benefits, Mercatus Center at George Mason University, 2012. Image reproduced with consent of publisher.

[21] Low doses are generally defined as below 10 rem (100 mSv). Nuclear Regulatory Commission, "Linear No-Threshold Model and Standards for Protection Against Radiation," proposed rule, *Federal Register*, Vol. 86, No. 156 (August 17, 2021), p. 45926, https://www.federalregister.gov/documents/2021/08/17/2021-17475/linear-no-threshold-model-and-standards-for-protection-against-radiation.

[22] Health Physics Society, "Episode 11: Creation of the Biological Effects of Atomic Radiation (BEAR) I Committee," *The History of the Linear No-Threshold Model (LNT)*, https://www.youtube.com/watch?v=7f99cSK0lQc.

[23] Health Physics Society, *The History of the Linear No-Threshold (LNT) Model*, https://hps.org/hpspublications/historylnt/episodeguide.html.

[24] Daniel I. Portess, George Bauer, Mark A. Hill, and Peter O'Neill, "Low-Dose Irradiation of Nontransformed Cells Stimulates the Selective Removal of Precancerous Cells via Intercellular Induction of Apoptosis," *Cancer Research*, Vol. 67, No. 3 (2007), pp. 1246-1253, https://doi.org/10.1158/0008-5472.CAN-06-2985.

The basics of LNT

The LNT model is the default dose-response model used to evaluate the risks associated with exposure to ionizing radiation, which refers to radiation strong enough to strips electrons from atoms. Radiation from nuclear power plants is one source of ionizing radiation. Other forms of ionizing radiation come from naturally occurring sources, such as radon gas or cosmic sources, as well as from man-made sources, such as X-rays. People even receive doses of ionizing radiation from sources emanating from within the human body.[25]

The LNT model enters into risk assessment during step two of the risk assessment process: the dose-response assessment. There are three main characteristics, or implications, of the LNT model. These are:[26]

- No dose at which risk is zero: LNT implies that even the smallest amount of exposure to a hazard has the potential to cause harm. LNT is sometimes called the "one-hit" model, because exposure to one molecule is considered enough to cause cancer or some other negative health endpoint. With LNT, there is no threshold below which exposure is free of risk.
- Risk is proportional to dose. The risk of adverse health effects rises proportionally as the exposure increases. For example, doubling the dose might double the associated cancer risk.
- Risk is additive: Cumulative exposure over time adds up in terms of risk. Therefore, receiving a small dose repeatedly over a protracted period of time has the same effect as receiving a large dose of the same magnitude all at once. Implicit in this assumption is there is little or no DNA repair mechanism at work to restore damaged cells.

For LNT to be a scientifically valid model to characterize risks, all three assumptions must be true. In the case of radiation, there are strong reasons to doubt all three.[27] For example, there is evidence of a threshold level below which effects from exposure to radiation are indistinguishable from those generated at background levels.[28] Furthermore, DNA repair mechanisms overcome cell damage that occurs at very low exposure levels.[29] Indeed, without such repair mechanisms, life on earth would not have been able to develop.[30]

LNT is also inconsistent with areas of the planet with high background radiation, such as Denver, Colorado or Kerala, India.[31] People in these areas receive chronic exposure to radiation over long periods of time, and this has resulted in a number of cancer cases far below what LNT would predict.[32]

In spite of these empirical challenges, many scientists, regulatory agencies, and scientific bodies defend the biological plausibility of LNT.[33] Much of this support stems from the 2006 Board on Radiation Effects Research BEIR VII report,[34] which endorsed the use of LNT, as well as reports from the National Council on Radiation Protection and Measurements (NCRP).[35]

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25 "3. What Are the Sources of Ionizing Radiation," Environmental Sciences Training Center, Rutgers: The State University of New Jersey, https://www.nj.gov/dep/rpp/llrw/download/fact03.pdf.

26 Jack Devanney, *Why Nuclear Power Has Been a Flop* (Tavernier, Florida: CTX Press, 2020).

27 See, for example, Cardarelli II and Ulsh, "It Is Time to Move Beyond the Linear No-Threshold Theory for Low-Dose Radiation Protection;" J.S. Welsh, Bill Sacks and Jeffry A. Siegel, "Time to Eliminate LNT: The NRC Needs to Adopt LT and Eliminate ALARA," *Nuclear Medicine and Biomedical Imaging*, Vol. 2, no. 1 (2017), pp. 1-5, https://doi.org/10.15761/NMBI.1000118; see generally, Health Physics Society, *The History of the Linear No-Threshold (LNT) Model* video series.

28 Bobby R. Scott and Sujeenthar Tharmalingam, "The LNT Model for Cancer Induction Is Not Supported by Radiobiological Data," *Chemico-Biological Interactions*, Vol. 301, (2019), pp. 34–53, https://doi.org/10.1016/j.cbi.2019.01.013.

29 Bill Sacks, Gregory Meyerson and Jeffry A. Siegel, "Epidemiology Without Biology: False Paradigms, Unfounded Assumptions, and Specious Statistics in Radiation Science," *Biological Theory*, Vol. 11 (2016), pp. 69–101, https://doi.org/10.1007/s13752-016-0244-4.

30 David Costantini and Benny Borremans, "The Linear No-Threshold Model Is Less Realistic than Threshold or Hormesis-Based Models: An Evolutionary Perspective," *Chemico-Biological Interactions* Vol. 301 (2019), pp. 26–33, https://doi.org/10.1016/j.cbi.2018.10.007.

31 Brian Wang, "Fukushima Had Less Radiation Outside the Plant than Kerala Background Radiation Levels," Energy Central, November 11, 2019, https://energycentral.com/c/ec/fukushima-had-less-radiation-outside-plant-kerela-background-radiation-levels.

32 Devanney, *Why Nuclear Power Has Been a Flop.*

33 See, for example, National Research Council, *Health Risks from Exposure to Low Levels of Ionizing Radiation: BEIR VII Phase 2* (Washington, DC: The National Academies Press, 2006), https://nap.nationalacademies.org/catalog/11340/health-risks-from-exposure-to-low-levels-of-ionizing-radiation; International Commission on Radiological Protection, "ICRP Publication 99: Low-dose Extrapolation of Radiation-related Cancer Risk," *Annals of the ICRP*, Vol. 35, No. 4 (2005), https://www.icrp.org/publication.asp?id=ICRP%20Publication%2099; John D. Boice Jr., "The Linear Nonthreshold (LNT) Model as Used in Radiation Protection: An NCRP Update," *International Journal of Radiation Biology*, Vol. 93, No. 10 (2017), pp. 1079-1092, https://doi.org/10.1080/09553002.2017.1328750; Bemnet Alemayehu, "Hold Fast to Linear No-Threshold for Radiation Protection," Natural Resources Defense Council, July 13, 2016, https://www.nrdc.org/bio/bemnet-alemayehu/hold-fast-linear-no-threshold-radiation-protection.

34 National Research Council, *Health Risks from Exposure to Low Levels of Ionizing Radiation: BEIR VII Phase 2.*

35 National Council on Radiation Protection and Measurements, "Implications of Recent Epidemiologic Studies for the Linear Nonthreshold Model and Radiation Protection," Commentary 27, April 24, 2018, https://doi.org/10.1088/1361-6498/aad348.

The basis of their defense has been strongly criticized, however.[36] For example, BEIR VII acknowledges that risk estimation below 100 millisieverts (mSv)—a measure of radiation dose—is not possible with current epidemiological data, and subsequent research has cast doubt on many of the conclusions of this report.[37] The National Academy of Sciences Committee on Biological Effects of Ionizing Radiation, which authored the report, also controversially kicked off a member of the committee in 1999 who had expressed skepticism of LNT a few years earlier.[38] Meanwhile, NCRP reports have also been the subject of substantial criticism, including cherry-picking evidence, circular reasoning and, ignoring or suppressing contrary evidence.[39]

At a minimum, it is fair to say that at present there is no scientific consensus as to which dose-response model is most scientifically valid. However, it is also fair to say that there is substantial evidence to support that low-level radiation is either safe or beneficial, as research on repair mechanisms has come to light in recent decades.

However, the LNT model is not only defended on scientific grounds. It is also advanced in a risk management context to justify a "conservative" or "prudent" stance to protecting public health and safety. This regulatory stance is grounded in the precautionary principle, and it is this defense of LNT that explains why federal agencies like NRC, as well as other agencies within the US federal government, continue to rely on the LNT, even as the science supporting it has gradually eroded.

LNT's troubled history

The LNT model's history provides a case study of how policy judgments can often become intermingled with science. A dose-response model can be used in two ways. It can be used in a *positive* context to objectively describe data observed between exposure to a human health hazard and the health response. Or, it can be used in a *normative* risk management role when setting regulatory standards. The first role is one where expertise can play a role in shaping our understanding of environmental hazards. The second is a purely policy role where scientific expertise may not provide much guidance.

In risk assessment, often the data available are limited and cannot objectively characterize the full nature of a risk. Indeed, the primary role of a dose-response model is to distill a complex relationship, where data are either unavailable or imperfect, into a simplified and more usable form. Data limitations occur because evidence of human exposure to a hazard is unavailable, is confounded by a variety of other health factors in people's environments, is only available from animal studies that may have limited applicability to humans, or is only available in humans at high exposure levels that may not be representative of health effects at low exposure levels.[40] Combined, these problems lead to substantial uncertainty about the plausibility of any dose response model.

This leads to a dilemma. Scientists are often put in the uncomfortable position of having to make assumptions about important policy-relevant variables under conditions where uncertainty precludes them from being able to provide scientifically-grounded conclusions. Scientists settled on the LNT in part for its simplicity, but also because of its tendency to estimate an upper-bound limit on risk in the low-dose

[36] John J. Cardarelli II and Brant A. Ulsh, "It Is Time to Move Beyond the Linear No-Threshold Theory for Low-Dose Radiation Protection;" Brant A. Ulsh, "A Critical Evaluation of the NCRP COMMENTARY 27 Endorsement of the Linear No-Threshold Model of Radiation Effects," *Environmental Research*, Vol. 167 (2018), pp. 472–487, https://doi.org/10.1016/j.envres.2018.08.010.

[37] Cardarelli II and Ulsh, "It Is Time to Move Beyond the Linear No-Threshold Theory for Low-Dose Radiation Protection."

[38] See Letter from Raymond Johnson, President of the Health Physics Society, to E. W. Colglazier, Executive Officer of the National Academy of Sciences, November 11, 1999, available from the author upon request. See also, Kenneth L. Mossman, Marvin Goldman, Frank Masse, William A. Mills, Keith J. Schiager, Richard L. Vetter, "Health Physics Society* Position Statement," Health Physics Society, March 1996, https://naygn.org/wp-content/uploads/2013/09/Radiation-Risk-In-Perspective-HPS.pdf. The 1996 position statement was co-authored by Dr. Mossman, and may have contributed to his removal from the BEIR VII committee.

[39] Ulsh, "A Critical Evaluation of the NCRP COMMENTARY 27 Endorsement of the Linear No-Threshold Model of Radiation Effects."

[40] Richard Belzer, "Risk Assessment, Safety Assessment, and the Estimation of Regulatory Benefits, Mercatus Center at George Mason University, 2012, https://www.mercatus.org/research/research-papers/risk-assessment-safety-assessment-and-estimation-regulatory-benefits.

zone.[41] This set of circumstances unfortunately created conditions for considerable mischief. Radiation risk assessment has historically been influenced by a variety of political and ideological forces.[42]

The adoption of the LNT model as the default model for radiation risk assessment in the mid-20th century was at least partially motivated by an agenda by scientists who wanted to put an end to above-ground nuclear testing in the United States.[43] In some cases, scientists were willing to stretch the truth to advance their ideas or agendas. For example, Nobel laureate Hermann Muller, an early proponent of LNT, did not reveal known, pertinent evidence that did not support LNT during his Nobel Prize speech.[44] Scientific bodies like the first BEAR committee organized by the National Academies of Sciences were compromised by ideological and financial conflicts of interest.[45] One of the most influential scientific papers to impact public policy in this area has significant shortcomings with respect to the data used, which were known by the author but not revealed upon publication.[46]

Other conflicts of interest and scientific shortcomings have been uncovered in subsequent academic research in recent years.[47] Much of this history is beyond the scope of the current paper, and has been explored in detail elsewhere. It is clear that many of the reasons the LNT model became the default model for radiation risk assessment were not grounded in scientific evidence, but rather were ideological in nature or motivated by the self-interest of scientists.[48]

That the history of the adoption of LNT includes gross incompetence, as well as scientific misconduct and perhaps even fraud,[49] does not necessarily mean LNT is incorrect from the standpoint of being scientifically valid. However, LNT's history does give us reasons to be skeptical of the model's validity, as well as of the motivations of the scientists who promoted the model at a critical time in its history. Unfortunately, unacceptable behavior on the part of scientists continues in the present.

In the last several years, a covert campaign was conducted by government bureaucrats, a former president of the Health Physics Society, and members of the Board of Directors of the Health Physics Society and NCRP, to discredit those who seek to cast a light on the LNT model's historical foundations. There was an attempt by individuals from these groups to overthrow the leadership of the Health Physics Society because it was viewed as being anti-LNT.

After this inappropriate behavior was uncovered through various Freedom of Information Act requests, and brought to light in a blog post,[50] the president of the Health Physics Society requested an oversight

41 "The linear nonthreshold model for somatic effects was introduced and quantified gradually between 1950 and 1964 with special reference to the biopolitical necessity for making quantitative estimates of the maximum effects of world-wide fallout from the atmospheric testing of nuclear weapons. The linear nonthreshold model was specifically chosen on a basis of mathematical simplicity and prudence to represent the upper limit of risk in the low-dose domain, for somatic radiobiological effects which had been observed only in a higher-dose domain. The linear nonthreshold model was not based on radiobiological data for somatic effects in the low- dose domain." See Health Physics Society, Message from President Dade W. Moeller, October Newsletter, October 15, 1971. Available from the author upon request.

42 Edward J. Calabrese, "The Linear No-Threshold (LNT) Dose Response Model: A Comprehensive Assessment of Its Historical and Scientific Foundations." *Chemico-Biological Interactions*, Vol. 301 (2019), pp. 6–25, https://doi.org/10.1016/j.cbi.2018.11.020.

43 Rod Adams, "Motives for Pushing a No-Threshold Dose Radiation Risk Model (LNT) in 1955-56," NuclearNewswire, August 26, 2014, https://www.ans.org/news/article-1617/motives-for-pushing-a-no-threshold-dose-radiation-risk-model-lnt-in-1955-56/; Health Physics Society, "Episode 10: The Birth of LNT Activism," *The History of the Linear No-Threshold (LNT) Model*, https://www.youtube.com/watch?v=D2Tmvc8awZQ.

44 Edward J. Calabrese, "Muller's Nobel Prize Lecture: When *Ide*ology Prevailed Over Science," *Toxicological Sciences*, Vol. 126, No. 1 (2012), pp. 1–4, https://doi.org/10.1093/toxsci/kfr338.

45 Ed Calabrese, "Societal Threats from Ideologically Driven Science," *Academic Questions* Vol. 30 (2017), pp. 405–418, https://www.nas.org/academic-questions/30/4/societal_threats_from_ideologically_driven_science; Health Physics Society, "Episode 11: Creation of the Biological Effects of Atomic Radiation (BEAR) I Committee."

46 Edward B. Lewis, "Leukemia and Ionizing Radiation," *Science*, Vol. 125, No. 3255 (1957), pp. 965-972, https://doi.org/10.1126/science.125.3255.965; Health Physics Society, "Episode 16: The Most Important Paper in Cancer Risk Assessment That Affects Policy in the US," *The History of the Linear No-Threshold Model (LNT) Model*, https://www.youtube.com/watch?v=NNdF1-K6my4.

47 Paul B. Selby and Edward J. Calabrese, "How Self-Interest and Deception Led to the Adoption of the Linear Non-Threshold Dose Response (LNT) Model for Cancer Risk Assessment," *Science of the Total Environment*, Vol. 898 (2023), p. 165402, https://doi.org/10.1016/j.scitotenv.2023.165402; Ed Calabrese and Paul Selby, "Muller Mistakes: The Linear No-Threshold (LNT) Dose Response and US EPA's Cancer Risk Assessment Policies and Practices," *Chemico-Biological Interactions*, Vol. 383 (2023), p. 110653, https://doi.org/10.1016/j.cbi.2023.110653.

48 Health Physics Society, *The History of the Linear No-Threshold (LNT) Model*.

49 John Cardarelli II, Barbara Hamrick, Dan Sowers, and Brett Burk, "The History of the Linear No-Threshold Model and Recommendations for a Path Forward," *Health Physics*, Vol. 124, No. 2 (2023), p. 131-135, https://DOI.org/10.1097/HP.0000000000001645.

50 JunkScience.com, "Emails Reveal: Bureaucrats censor radiation risk science fraud by cancelling whistleblowers; Huge implications for nuclear power and more;" Zoom.com, Thomas Johnson's Personal Meeting Room - Shared screen with speaker view, https://us02web.zoom.us/rec/share/DpYO4wCcswvi8VanOf7vHsAriSVf_6vx20VtomCNGyM6nlTTzEhkW6Dv4UMZ_yOj.sLcOEwqd63adNVfM?startTime=1692920671000.

investigation from members of Congress.[51] Following this, the Board of Directors of the Health Physics Society, some of whom were cast in a negative light in the revealed emails, censured the president, in an apparent act of retaliation.[52] The censure was later overturned after it was put to a vote before the membership of the Health Physics Society.[53]

It is not hard to see why activist scientists might be drawn to the LNT model. The LNT model is often argued to be "conservative" in the sense that it likely errs on the side of overestimating,[54] rather than underestimating, risks in the low dose range.[55] Even if alternatives to LNT may have better predictive accuracy, many scientists may view themselves as having an obligation to protect public health.[56] In their view, supporting LNT takes an approach to risk management that says it is "better to be safe than sorry."[57]

In addition to these perhaps well-intentioned but misguided concerns, there are various political economy and reputational reasons that explain LNT's popularity. These reasons include institutional inertia (the model has become entrenched at regulatory agencies and scientific bodies that are resistant to change), professional politics (careers and reputations of many senior officials and scientists are tied to the LNT model), power preservation (LNT gives regulators considerable flexibility to restrict radiation exposure), legal liability (admitting mistakes could lead to blame and financial or legal repercussions as a result),[58] and public perception (being seen as weakening standards could undermine agency credibility and trust).[59]

In addition to these reasons, there is the practical consideration of regulators having to review all of the regulations that are based on the LNT model if the default dose-response model for radiation changes. Many regulators do not want to have to do this hard work.[60]

Making matters more complicated, the LNT model was taken from the field of radiation genetics, where it originated, and then used as the default model for carcinogens more generally and also for some non-cancerous chemicals and agents.[61] Thus, the conservative or precautionary emphasis of LNT is now widespread in risk assessment across many domains and hazards, not just radiation.

[51] Letters from John J. Cardarelli II, President of the Health Physics Society, to Members of Congress, "Request for an Oversight Investigation to Ensure that the Latest Science is Incorporated into the Radiation Protection Standards for Low-Dose Environment," June 5 and 7, 2023, https://hps.org/documents/Cardarelli_letter_to_DC_leaders_vers7_5June2023.pdf and https://hps.org/documents/Cardarelli_letter_to_DC_leaders_vers7a_7June2023.pdf.

[52] Healthphysics.com, "Censure the Censors," Healthphysicsblog.com, October 17, 2023, https://www.healthphysics.blog/p/censure-the-censors.

[53] Health Physics Society, "Health Physics News Digest," November, 2023, https://hps.org/hpspublications/newsletter.html.

[54] Albert L. Nichols and Richard J. Zeckhauser, "The Dangers of Caution: Conservatism in Assessment and the Mismanagement of Risk," in *Advances in Applied Micro-economics* (V. Kerry Smith, ed.) Vol. 4, (1986), pp. 55-82.

[55] Terje Aven, "On the Use of Conservatism in Risk Assessments," *Reliability Engineering & System Safety*, Vol. 146, (February 2016), pp. 33-38, https://doi.org/10.1016/j.ress.2015.10.011.

[56] Adam M. Finkel, "Is Risk Assessment Really Too Conservative: Revising the Revisionists," *Columbia Journal of Environmental Law* Vol. 14 (1989), pp. 427-467, https://journals.library.columbia.edu/index.php/cjel/article/download/5779/2838.

[57] Carol L. Silva, Hank C. Jenkins-Smith, and Richard P. Barke, "Reconciling Scientists' Beliefs about Radiation Risks and Social Norms: Explaining Preferred Radiation Protection Standards," *Risk Analysis*, Vol. 27 (2007), pp. 755-773, https://doi.org/10.1111/j.1539-6924.2007.00919.x; Hank C. Jenkins-Smith, Carol L. Silva, and Christopher Murray, "Beliefs about Radiation: Scientists, the Public and Public Policy," *Health Physics*, Vol. 97 (2009), pp. 519-527, https://doi.org/10.1097/HP.0b013e3181ad7eec.

[58] An interesting research question, which is beyond the scope of this article, is the degree to which LNT has directly or indirectly influenced the liability regime surrounding the nuclear industry.

[59] Healthphysics.com, "Censure the Censors."

[60] See, for example, emails from Jonathan Edwards of EPA noting that "scores of regulations are written on [LNT] using it as a scientific basis." Junkscience.com, "Emails Reveal: Bureaucrats censor radiation risk science fraud by cancelling whistleblowers; Huge implications for nuclear power and more."

[61] Edward J Calabrese, "From Muller to Mechanism: How LNT became the Default Model for Cancer Risk Assessment," *Environmental Pollution*, Vol. 241 (2018), pp. 289-302, https://doi.org/10.1016/j.envpol.2018.05.051.

How NRC uses LNT

The LNT model has been central to radiation protection policies for decades, forming a cornerstone of the NRC's regulations setting "standards for protection against radiation."[62] The key areas affected by these regulations include: [63]

- Dose parameters for radiation workers and the general public
- The protocol for monitoring and labeling radioactive materials
- Safety directives and signage in radiation-prone zones
- Procedures for reporting the theft or loss of radioactive elements

These standards have been in place since 1991.[64] At that time, the NRC determined that it was prudent to assume the validity of the LNT model because of the considerable uncertainty surrounding the effects of ionizing radiation. The NRC's exact position is that "uncertainty and lack of consensus persists in the scientific community."[65] The agency states that authorities in the field of radiological risk acknowledge "health risks of radiation exposure can only be estimated with a reasonable degree of scientific certainty at radiation levels that are orders of magnitude greater than limits established by regulation for protection of the public."[66]

The NRC is charged under the Atomic Energy Act "with protecting the public from radiological harm."[67] Thus, "in the absence of convincing evidence that there is a dose threshold or that low levels of radiation are beneficial,"[68] the NRC believes LNT provides a basis for "a conservative radiation protection regulatory framework."[69] In other words, the NRC is quite clear that the way it employs the LNT model is in a *policy* context, through adoption of a "conservative" regulatory program.

The NRC is also clear that the LNT model is not a tool used by the agency for deterministic mortality projections.[70] In other words, it is not used to estimate deaths from exposure to radiation, but rather the NRC uses the LNT model to "set regulatory limits."[71] The NRC elaborates that "the LNT model is an assumption that likely cannot be scientifically validated by radiobiologic or epidemiologic evidence in the low-dose range."[72]

The NRC's rationale for relying on LNT thus hinges on its belief that "The LNT model provides for a conservative, comprehensive radiation protection scheme that protects individuals in all population categories (male, female, adult, child, and infant)."[73] While NRC does not use LNT to estimate cancer or mortality risks explicitly, even using LNT to set dose limits is problematic. These limits are presumably based on upper bounds of estimated radiation risk. Thus, NRC is assuming risks are present even when they are not.

Other federal agencies like the Environmental Protection Agency (EPA) also base regulatory limits and nonregulatory guidelines for public exposure on LNT.[74] At EPA, unlike NRC, LNT is used to estimate

[62] 10 C.F.R. Part 20.

[63] Nuclear Regulatory Commission, "Linear No-Threshold Model and Standards for Protection Against Radiation," p. 45924; see also Jerry M. Cuttler and Edward J. Calabrese, "What Would Become of Nuclear Risk if Governments Changed Their Regulations to Recognize the Evidence of Radiation's Beneficial Health Effects for Exposures That Are Below the Thresholds for Detrimental Effects?" *Dose-Response*, Vol. 19, No. 4 (2021), p. 1-6, https://doi: 10.1177/15593258211059317.

[64] Nuclear Regulatory Commission, "Linear No-Threshold Model and Standards for Protection Against Radiation," p.45923.

[65] Nuclear Regulatory Commission, "Linear No-Threshold Model and Standards for Protection Against Radiation," p. 45925. On the lack on scientific consensus regarding LNT, see also, Cardarelli II and Ulsh, "It Is Time to Move Beyond the Linear No-Threshold Theory for Low-Dose Radiation Protection."

[66] Nuclear Regulatory Commission, "Linear No-Threshold Model and Standards for Protection Against Radiation," p. 45925.

[67] Nuclear Regulatory Commission, "Linear No-Threshold Model and Standards for Protection Against Radiation," p. 45925.

[68] Nuclear Regulatory Commission, "Linear No-Threshold Model and Standards for Protection Against Radiation," p. 45925.

[69] Nuclear Regulatory Commission, "Linear No-Threshold Model and Standards for Protection Against Radiation," p. 45932.

[70] Nuclear Regulatory Commission, "Linear No-Threshold Model and Standards for Protection Against Radiation," p. 45932.

[71] Nuclear Regulatory Commission, "Linear No-Threshold Model and Standards for Protection Against Radiation," p. 45932.

[72] Nuclear Regulatory Commission, "Linear No-Threshold Model and Standards for Protection Against Radiation," p. 45926, citing the NCRP.

[73] Nuclear Regulatory Commission, "Linear No-Threshold Model and Standards for Protection Against Radiation," p. 45932.

[74] US Environmental Protection Agency, "Radiation Health Effects," accessed November 28, 2023, https://www.epa.gov/radiation/radiation-health-effects.

risks,[75] for example in the context of hazardous waste cleanup efforts.[76] Nevertheless, EPA, like NRC, acknowledges that its use of LNT to estimate risks is a policy decision,[77] as opposed to a matter of science.

One significant offshoot of the LNT model's guidance is the ALARA concept, which is an NRC policy that states that radiation exposure should be kept "As Low As Reasonably Achievable." ALARA, according to NRC regulations, means "making every reasonable effort to maintain exposures to radiation as far below the dose limits in this part as is practical consistent with the purpose for which the licensed activity is undertaken."[78] ALARA is consistent with the basic premise of LNT that no level of exposure is free of risk. Hence, regulated entities are required to continue reducing exposures levels even below those set in regulatory limits, whenever it is "reasonable" for them to do so.

ALARA's operationalization brings about excessive regulatory costs that in practice lead the agency to require methods of protection that may make the nuclear industry uncompetitive for few if any health benefits. For example, an MIT analysis exploring why nuclear construction costs often exceed projections found that tightening safety regulations played a significant role.[79]

For many years, these NRC practices have remained in place. Not surprisingly, over the years there have also been periodic calls for reevaluation. An important moment in the debate arrived in 2015, when three scientists affiliated with a group called Scientists for Accurate Radiation Information independently lodged petitions with the NRC. These petitioners argued that emerging scientific evidence provides reason to doubt the foundational reliability of the LNT model in radiation risk assessment. Evidence from the petitioners was eventually turned into a peer reviewed journal article.[80] In the wake of these petitions, the NRC invited comments on the issue from the scientific community, involved stakeholders, and the public at large.[81]

Following a review process, in 2021, the NRC opted to uphold the LNT model. The agency ultimately concluded, "The NRC's position remains unchanged from 1991."[82] A variety of domestic scientific bodies, including the National Academy of Sciences and the NCRP, as well as international bodies, like the International Commission on Radiological Protection (ICRP) and the International Atomic Energy Agency (IAEA), supported the continued use of the LNT model.[83] US federal agencies, including the Department of Health and Human Services and the EPA, also voiced their support for the LNT model during the public commenting process.[84]

However, given the NRC's own admission that the LNT model can't be scientifically validated, support from these scientific and regulatory bodies cannot be based on science. Their support must be perceived as a policy position, driven by a conservative stance and a pledge to uphold what they perceive as maximum safety. Moreover, the NRC and commenters who

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75 "...the cancer risk associated with a radionuclide intake or external exposure is calculated as the product of the appropriate cancer risk coefficient and the corresponding radionuclide intake or exposure. This calculation presumes that risk is directly proportional to intake or exposure, i.e., it follows a linear, no-threshold (LNT) model. Current scientific evidence does not rule out the possibility that the calculated risk at environmental exposure levels may be overestimates or underestimates. However, several recent expert panels (UNSCEAR, 1993, 1994; NRPB, 1993; NCRP, 1997) have concluded that the LNT model is sufficiently consistent with current information on carcinogenic effects of radiation that its use is scientifically justifiable for purposes of estimating risks from low doses of radiation. As a practical matter, the LNT approach is universally used for assessing the risk from environmental exposure to radionuclides as well as other carcinogens." See US Environmental Protection Agency, "Federal Guidance Report No. 13: Cancer Risk Coefficients for Environmental Exposure to Radionuclides," (Washington DC: September, 1999), https://www.epa.gov/sites/default/files/2015-05/documents/402-r-99-001.pdf.

76 See, for example, EPA's Preliminary Remediation Goals for Radionuclides (PRG) Calculator. According to US EPA, "PRGs are *risk-based*, *conservative* screening values to identify areas and contaminants of potential concern (COPCs) that may warrant further investigation" (emphasis added). Environmental Protection Agency, PRG Home, accessed November 30, 2023, https://epa-prgs.ornl.gov/radionuclides/.

77 "EPA has made the *policy decision* that risks from radionuclide exposures at remedial sites should be estimated in the same manner as chemical contaminants, which is consistent with EPA's remedial program implementing guidance" (emphasis added). LNT is the default dose-response model for chemical carcinogens. See, US Environmental Protection Agency, "Memorandum on Distribution of the 'Radiation Risk Assessment at CERCLA Sites: Q&A,'" (Washington, DC: June 13, 2013), https://semspub.epa.gov/work/HQ/176329.pdf.

78 Nuclear Regulatory Commission, "Linear No-Threshold Model and Standards for Protection Against Radiation," p. 45929.

79 Stauffer, "Building Nuclear Power Plants: Why Do Costs Exceed Projections?"

80 Welsh et al., "Time to eliminate LNT: The NRC Needs to Adopt LT and Eliminate ALARA."

81 Nuclear Regulatory Commission, "Linear No-Threshold Model and Standards for Protection Against Radiation," *Federal Register*, Vol. 80, No. 120 (August 21, 2015), pp. 50804–05, https://www.federalregister.gov/documents/2015/06/23/2015-15441/linear-no-threshold-model-and-standards-for-protection-against-radiation.

82 Nuclear Regulatory Commission, "Linear No-Threshold Model and Standards for Protection Against Radiation," p. 45925.

83 Nuclear Regulatory Commission, "Linear No-Threshold Model and Standards for Protection Against Radiation," p. 45932. Nuclear Regulatory Commission, "Linear No-Threshold Model and Standards for Protection Against Radiation," p. 45925.

84 Nuclear Regulatory Commission, "Linear No-Threshold Model and Standards for Protection Against Radiation," p. 45927.

supported LNT largely failed to directly engage with the scientific evidence conflicting with LNT.[85]

Furthermore, despite having supporters, the LNT model was not without its detractors. Numerous commenters challenged the LNT paradigm, proposing alternative dose-response models that might better reflect real-world radiation exposure dynamics. Ultimately, the NRC's use of the LNT model should be seen as how the agency chooses to interpret its statutory obligations under existing law. Other agencies, like the EPA, choose a similar interpretation to their own guiding statutes. For example, representatives of the EPA have stated:

> *The use of LNT for radiation protection purposes is often justified as being "conservative"; i.e., it is presumed that, while we may not be able to estimate the risk at low doses accurately, linear extrapolation is unlikely to (greatly) underestimate risk. Hence, if radiation standards are promulgated under the assumption that LNT is correct, they will be protective.*[86]

This interpretation should be seen as having its foundation in the precautionary principle. However, it will be shown that the assumption that LNT is protective on this basis is unfounded. Moreover, regulating under the guidance of the precautionary principle is but one interpretation of law, and policy makers in the future could easily interpret NRC and EPA's statutory and public health obligations differently, especially if the aim of these agencies is protecting public health.

Is the precautionary principle 'conservative'?

The precautionary principle is a concept that has been incorporated into an increasing number of international agreements and environmental statutes over the past few decades.[87] Essentially, the precautionary principle states that when an activity or technology may harm human health or the environment, precautionary measures should be taken even if some cause and effect relationships are not fully established scientifically.

The principle is sometimes summarized in the following way: "Where there are threats of serious and irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation."[88]

The precautionary principle is employed in a variety of areas, beyond just in an environmental context.[89] In risk assessment, like with many environmental challenges, there is also considerable uncertainty about cause and effect. Rather than wait for scientific debates to be settled, some believe precaution is warranted. The idea is that it is prudent that a risk should be assumed to be harmful. By extension, it is assumed something should be done about it in policy terms, even if science cannot currently provide conclusive evidence the risk is real.

The problem with this logic is relatively straightforward: Such a policy could easily increase risk rather than reduce it. For one thing, this strategy myopically focuses on reducing a target risk while ignoring any substitute risks. With nuclear power, one substitute risk includes any health risks associated with fossil fuel-based energy production. Another risk is grid reliability if new electricity generation is delayed or backup sources for less-reliable renewable energy sources are phased out without introducing any substitutes. Yet another risk is the risk of slowing innovation in nuclear technology.

If risks from nuclear power and radiation are overestimated, these substitute risks, which are usually ignored in risk assessment, may well increase risk on balance. This is not merely speculation. It appears to be precisely what has happened in

[85] For example, the EPA was criticized for overlooking 34 of 36 references cited by the NRC petitioners that conflicted with LNT. See EPA's comment to NRC, available at https://www.regulations.gov/document/NRC-2015-0057-0436; and Cardarelli II and Ulsh, "It Is Time to Move Beyond the Linear No-Threshold Theory for Low-Dose Radiation Protection."

[86] Jerome S. Puskin, "Perspective on the Use of LNT for Radiation Protection and Risk Assessment by the U.S. Environmental Protection Agency," *Dose-Response*, Vol. 7 (2009), pp. 284–291, https://www.epa.gov/radiation/perspective-use-lnt-radiation-protection-and-risk-assessment-us-environmental-protection.

[87] Kenneth L. Mossman and Gary E. Marchant, "The Precautionary Principle and Radiation Protection," *RISK*, Vol. 13, No. 1 (2002), pp. 137-149, https://scholars.unh.edu/cgi/viewcontent.cgi?article=1489&context=risk.

[88] UN Global Compact, "Principle 7," accessed November 14, 2023, https://unglobalcompact.org/what-is-gc/mission/principles/principle-7.

[89] Food safety is one area, but there are many others. See, for example, Gregory Conko, "Safety, Risk and the Precautionary Principle: Rethinking Precautionary Approaches to the Regulation of Transgenic Plants," *Transgenic Research*, Vol. 12 (2003), pp. 639-647, https://doi.org/10.1023/B:TRAG.0000005157.45046.8e.

countries like Germany that attempted to phase-out nuclear power.[90] Coal-fired electricity production increased following reductions in nuclear electricity production, leading to air pollution that otherwise would not have existed.

More problematic is if perceived hazards turn out not to be risky at all, or to have health benefits from exposure to them. The LNT model rules out the possibility of a threshold below which there is no discernible increase in risk from exposure. If a threshold model is correct, regulatory measures would have no health benefits beyond some point. Moreover, if a hormetic dose-response relationship turns out to be correct, exposure to radiation could reduce health risks by activating and increasing repair mechanisms.[91] In that case, regulatory measures could cause health harm.

A further reason why intentionally erring on the side of overestimating risk is not precautionary is because regulatory interventions are costly, and the costs of regulatory interventions also create novel risks. For example, regulations reduce incomes, and people are less able to mitigate risks in a private setting when they possess fewer resources.[92] Energy price spikes in Europe following Russia's invasion of Ukraine were associated with significant increases in mortality, perhaps because "expensive energy discourages people from adequately heating their homes, thereby increasing the risk of cardiac and respiratory problems due to prolonged exposure to cold conditions."[93] This reduced-income effect can lead to deaths that outnumber the deaths prevented by regulatory measures.

Thus, following the precautionary principle's guidance is only "conservative," in the sense of erring on the side of reducing overall risk under certain, relatively strict, conditions. These conditions include when risks are actually present at low doses and when substitute risks, including from regulatory costs, are relatively low. As one study put it, "When government overstates risk, it is not protecting the public and in fact can encourage decisions that are harmful to both people and the environment."[94]

Again, this is not mere speculation, as there are numerous instances of precautionary policies and practices doing more harm than good. For example, golden rice is a rice that has been genetically engineered to produce beta-carotene and address vitamin A deficiency. Some estimates suggest regulatory setbacks delayed a final product from coming to market by as much as ten years, preventing mass production of a life-saving grain and costing countless lives in the developing world.[95]

It is estimated that evacuation efforts following the nuclear accident in Fukushima, Japan led to more than 2,000 avoidable deaths.[96] Yet the Fukushima accident itself involved no deaths directly related to radiation exposure.[97] This is a case where LNT-guided policy caused harm, and it is not the only example. Tens of thousands, and perhaps even hundreds of thousands, of abortions occurred across Europe following the Chernobyl accident,[98] despite there being no evidence of radiation exposure leading to birth defects in humans.

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90 Stephen Jarvis, Olivier Deschenes and Akshaya Jha, "The Private and External Costs of Germany's Nuclear Phase-Out," *Journal of the European Economic Association*, Vol. 20, No. 3 (2022), pp. 1311–1346, https://doi.org/10.1093/jeea/jvac007.

91 Jonathan Baldwin and Vesper Grantham, "Radiation Hormesis: Historical and Current Perspectives," *Journal of Nuclear Medicine Technology*, Vol. 43, No. 4 (2015), pp. 242-246, https://doi.org/10.2967/jnmt.115.166074.

92 James Broughel and W. Kip Viscusi, "The Mortality Cost of Expenditures," *Contemporary Economic Policy*, Vol. 39, No. 1 (2021), pp. 156-167, https://doi.org/10.1111/coep.12483.

93 James Broughel, "The Lethal Impact of Rising Energy Prices," Competitive Enterprise Institute, June 26, 2023, https://cei.org/blog/the-lethal-impact-of-rising-energy-prices/.

94 Daren Bakst and Katie Tubb, "A Proactive Environmental Policy Agenda for Congress and the Administration," Heritage Foundation Backgrounder No. 3555, November 2, 2020, https://www.heritage.org/environment/report/proactive-environmental-policy-agenda-congress-and-the-administration.

95 James Broughel, "Rules for Robots: A Framework for AI Governance," Competitive Enterprise Institute, 2023, p. 15, https://cei.org/studies/rules-for-robots-a-framework-for-governance-of-ai/.

96 Brant Ulsh and Edward Calabrese, "Time for Radiation Regulation to Evolve," *Regulation* (Fall 2019), pp. 8-9, https://www.cato.org/regulation/fall-2019/time-radiation-regulation-evolve.

97 Cardarelli II and Ulsh, "It Is Time to Move Beyond the Linear No-Threshold Theory for Low-Dose Radiation Protection;" See also, Ulsh, "A critical evaluation of the NCRP COMMENTARY 27 endorsement of the linear no-threshold model of radiation effects."

98 Becky Ferreira, "Why Hundreds of Thousands of Women Ended Their Pregnancies After Chernobyl," Vice, June 3, 2019, https://www.vice.com/en/article/ywyqzv/why-hundreds-of-thousands-of-women-ended-their-pregnancies-after-chernobyl.

Similarly, billions of dollars have been spent cleaning up contaminated sites unnecessarily.[99] These are funds that could have been deployed elsewhere, for example on combatting cases of c-difficile,[100] MRSA,[101] or the flu,[102] which together account for about 50,000 to 90,000 deaths per year in the United States.

In the context of medical imaging, members of the public sometimes fear a risk of cancer and therefore refuse beneficial diagnostic X-rays that would otherwise uncover unknown health ailments.[103] Yet another example comes from irradiation of food, which is a food safety process that uses radiation to kill germs that can cause food poisoning.[104] These examples highlight how fear of radiation often results in overreaction and unsound policy, and how LNT provides a veneer of scientific credibility to such fear.

Taken together, these examples highlight how the precautionary principle is often not the most prudent course of action from a risk management perspective. Any interpretation that LNT is protective would appear to be in conflict with, for example, EPA's scientific integrity policy that "The environmental policies, decisions, guidance, and regulations that impact the lives of all Americans every day *must be grounded, at a most fundamental level, in sound, high quality science"* (emphasis added).[105] Similarly, the use of LNT seems to fall short of standards set in NRC's information quality guidelines, which state "the NRC will impose the highest level of quality on influential scientific, financial, or statistical information, which the agency defines as information that forms the technical basis for a substantive rulemaking that has substantial impact on an industry."[106]

Scholars Charles Pennington and Jeffry Siegel sum up the evidence on LNT well, when they state the "claim of 'prudence' is a dangerously ill-informed illusion, failing to consider a range of possible outcomes."[107] Yet, senior management at the EPA state the LNT policy is "set in stone" and that the agency would "never subscribe to" "opening it up for policy review."[108] Such claims are not only antithetical to science, they are dangerous given the numerous ways in which the precautionary principle can increase risks.

In the context of radiation, there is not sufficient information to disprove beyond a doubt that the LNT is not valid.[109] However, usually in science a null hypothesis is assumed by default. The Health Physics Society, a respected academic organization, notes that "below levels of about 100 mSv above background from all sources combined, the observed radiation effects in people are not statistically different from zero." In the absence of compelling evidence, a threshold model should be the default for radiation rather than LNT. Indeed, the "burden of proof lies with those asserting the LNT model is correct, not on those asserting the null hypothesis of no effect at low doses."[110]

A course correction at federal agencies like NRC and EPA is consistent with sound science, as well as consistent with protecting public health and a commitment to upholding the law. Such a course correction would first and foremost involve grounding decisions in reasoning other than the precautionary principle. On a more practical level, federal agencies

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99 Government Accountability Office, "Hanford Cleanup: Alternative Approaches Could Save Tens of Billions of Dollars," GAO-23-106880, Sep 28, 2023, https://www.gao.gov/products/gao-23-106880/.

100 Paul Feuerstadt, Nicolette Theriault and Glenn Tillotson, "The Burden of CDI in the United States: A Multifactorial Challenge," *BMC Infectious Diseases*, Vol. 23, No. 132 (2023), pp. 1-8, https://doi.org/10.1186/s12879-023-08096-0.

101 Harvard Medical School, "MRSA: The Not-So-Famous Superbug," Harvard Health Blog, September 12, 2016, https://www.health.harvard.edu/blog/mrsa-the-not-so-famous-superbug-2016091210191.

102 "Disease Burden of the Flu," Centers for Disease Control and Prevention, accessed November 29, 2023, https://www.cdc.gov/flu/about/burden/index.html.

103 Jeffry A. Siegel, Charles W. Pennington and Bill Sacks, "Subjecting Radiologic Imaging to the Linear No-Threshold Hypothesis: A Non Sequitur of Non-Trivial Proportion," *Journal of Nuclear Medicine*, Vol. 58, No. 1 (2017), pp. 1-6, https://doi.org/10.2967/jnumed.116.180182.

104 "Food Irradiation," Centers for Disease Control and Prevention, accessed November 27, 2023, https://www.cdc.gov/foodsafety/communication/food-irradiation.

105 US Environmental Protection Agency, "Scientific Integrity Policy," 2012, https://www.epa.gov/scientific-integrity/epas-scientific-integrity-policy.

106 Nuclear Regulatory Commission, "NRC Information Quality Guidelines," *Federal Register,* Vol. 67, No. 190 (October 1, 2002), pp. 61695-61699, https://www.nrc.gov/public-involve/info-quality/fr67p61695.html.

107 Charles W. Pennington and Jeffry A. Siegel, "The Linear No-Threshold Model of Low-Dose Radiogenic Cancer: A Failed Fiction," *Dose-Response,* Vol. 17, No. 1 (2019), p. 9, https://doi.org/10.1177/1559325818824200.

108 Junkscience.com, "Emails Reveal: Bureaucrats censor radiation risk science fraud by cancelling whistleblowers; Huge implications for nuclear power and more," June 2, 2023, https://junkscience.com/2023/06/emails-reveal-radiation-safety-establishment-tries-to-censor-blockbuster-debunking-of-the-lnt-and-cleanse-the-health-physics-society-of-lnt-critics/.

109 Health Physics Society, "Radiation Risk in Perspective: Position Statement of the Health Physics Society," 2019, https://hps.org/documents/radiationrisk.pdf.

110 Cardarelli II and Ulsh, "It Is Time to Move Beyond the Linear No-Threshold Theory for Low-Dose Radiation Protection."

should work to harmonize radiation protection standards in the United States with those of the rest of world by adopting ICRP recommendations.[111]

Conclusion and policy implications

The use of the LNT model for radiation risk assessment has a long and complex history.[112] The LNT model emerged in the midst of a heated battle surrounding above-ground nuclear testing. Its scientific basis has always been in doubt, given the limited data on health effects from low-dose exposure to radiation. Its attraction to scientists has always been at least partly political.

The LNT model's real popularity likely rests upon its close connection to the precautionary principle as well as its ability to represent powerful emotions that arise from fear of radiation. One study succinctly captured the point as follows:

> *Fear is an emotional reaction that can be helpful if real and present danger occurs but can be very debilitating and detrimental if it has no basis in reality. Radiation, if delivered at high doses, can indeed be dangerous. But at low doses, the kind we experience in almost all facets of life, including major nuclear accidents, such exposure is simply not to be feared.*[113]

As research has progressed, legitimate questions have been raised both about the LNT model's scientific plausibility as well as its reasonableness as a normative framework to guide policy. Yet the model has remained a cornerstone of risk assessment practices, in part due to sheer regulatory inertia.[114] Given the history of attempts to silence dissenting voices, as well as the tendency to overlook evidence that conflicts with prevailing views within regulatory institutions, Congress may want to conduct an independent oversight investigation to ensure the latest science is being used to develop radiation protection policies.[115]

Although a variety of scientific bodies and regulatory agencies continue to support the LNT, the adoption and application of the LNT model for risk assessment purposes was originally and remains today based on the precautionary principle, not scientific truth. While the LNT model continues to be used by federal agencies like the NRC, this is acknowledged to be a policy decision, based on a purportedly conservative regulatory stance that is not really conservative at all once one realizes the limitations of the precautionary principle.

Regulations will always be crafted based on a variety of priorities, scientific evidence being one of them. To the extent possible, regulations should be biology-based in the sense that they should not conflict with known scientific facts, like risks from radiation in parts of the world with high background levels. Today, regulations should be crafted in a manner that recognizes that human cells have the capacity to repair genetic and other damage.[116]

While factors beyond science can and should play a role in decision-making, these risk management factors should be kept separate from risk assessment to the extent feasible. Ideology can play a role in policy decisions, but it should not affect how risk assessors go about their practice. Nor is the precautionary principle conservative or erring on the side of caution. Rather, it is a philosophy that chooses to single out some considerations over others.

The dose response models used by risk assessors should be those that best agree with the totality of the available data, as well as perhaps be based on normative criteria when the evidence is insufficient to draw hard scientific conclusions. A potential path forward for dose-response purposes is to harmonize estimates from the major-known dose-response

111 Recommended dose limits from the ICRP are 1 to 20 mSv per year, depending on whether exposures relate to the public or for occupations. Some, though not all, US standards deviate from this benchmark. See M. Kai, T. Homma, J. Lochard, T. Schneider, J.F. Lecomte, A. Nisbet, S. Shinkarev, V. Averin, T. Lazo, "ICRP Publication 146: Radiological Protection of People and the Environment in the Event of a Large Nuclear Accident, Update of ICRP Publications 109 and 111," *Annals of the ICRP*, Vol. 49, No. 4 (2020), pp. 11-135, https://www.icrp.org/publication.asp?id=ICRP%20Publication%20146.

112 Health Physics Society, *The History of the Linear No-Threshold Model (LNT) Model*, https://hps.org/hpspublications/historylnt/episodeguide.html.

113 Brooks et al., "How the Science of Radiation Biology Can Help Reduce the Crippling Fear of Low-level Radiation."

114 Ulsh, "A Critical Evaluation of the NCRP COMMENTARY 27 Endorsement of the Linear No-Threshold Model of Radiation Effects."

115 See Letters from Cardarelli II to Members of Congress, "Request for an Oversight Investigation to Ensure that the Latest Science is Incorporated into the Radiation Protection Standards for Low-Dose Environments."

116 Health Physics Society, "Episode 22: Making Sense of History and a Path Forward by Dr. Calabrese," *The History of the Linear No-Threshold Model (LNT) Model*, https://www.youtube.com/watch?v=L3ZfL4vTPPM.

models, which include the LNT, threshold, and hormetic models.[117]

Concepts informed by LNT, such as the ALARA standard, should be abandoned. One option would be to replace ALARA with a Reasonableness in Optimization of Protection standard, which "requires consideration of all factors involved in standards, not just the radiation dose."[118] Other relevant factors include the costs of safety efforts and the risks associated with any substitutes to the hazard in question.

Alternatively, regulators could establish stopping points for ALARA, or a de minimis dose, below which regulation and safety measures can stop.[119] One challenge with the latter strategy is that adopting such a standard appears to contradict past agency actions that saw no safe level of exposure, thereby undermining agency credibility. Another option would be to align radiation dose limits found in regulations in the United States with those in international standards, including from the ICRP.[120]

While it is understandable that risk-averse regulators and scientific bodies may have strong policy views in light of their commitment to protecting public health, these entities have no particular expertise or authority when it comes to disputes based on policy grounds. Nor do they appear to recognize the considerable risk tradeoffs policymakers are confronted with when setting regulatory standards.

It is inappropriate for scientists to weigh in on what are essentially policy questions. This blurring of lines between risk assessment and risk management, between science and science policy, acts to the detriment of science as it undermines the integrity of the scientific process.

In light of the significant limitations of the LNT model, as well as America's constantly changing energy needs, there is no reason to treat past judgments as dispositive. Only through continuous re-evaluation can Americans trust that regulatory standards are not only scientifically sound, but aligned with their policy priorities and values as well.

About the author

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[117] Health Physics Society, "Episode 22: Making Sense of History and a Path Forward by Dr. Calabrese," *The History of the Linear No-Threshold (LNT) Model*, https://www.youtube.com/watch?v=L3ZfL4vTPPM; See also, Edward J Calabrese , Dima Yazji Shamoun, and Jaap C. Hanekamp, "Cancer Risk Assessment: Optimizing Human Health through Linear Dose-Response Models," *Food and Chemical Toxicology*, Vol. 81 (2015), pp. 137-140, https://doi.org/10.1016/j.fct.2015.04.023.

[118] Brooks et al., "How the Science of Radiation Biology Can Help Reduce the Crippling Fear of Low-level Radiation."

[119] Brant Ulsh and Edward Calabrese, "Time for Radiation Regulation to Evolve."

[120] See M. Kai et al., "ICRP Publication 146: Radiological Protection of People and the Environment in the Event of a Large Nuclear Accident, Update of ICRP Publications 109 and 111."

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