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Date of submission: 2 April 2023

Title of submission: Rethinking low-level radiation risks: The Linear Non-Threshold (LNT) Model for radiation and its scientific validity.

I am a candidate for the degree: PhD Nuclear Energy Futures

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Biosketch (approximately 150 words)

Sannah van Balen is a first-year PhD student in the Nuclear Energy group at the Engineering Department, University of Cambridge. Her research explores the risk and the perception of risk surrounding nuclear science and technology. Her current focus is on combining knowledge and insight from sociology, health science, and engineering to investigate how radiation risks are assessed and managed within the nuclear sector.

Previously based in the Netherlands, she worked as an energy transition consultant to Dutch industry and policymakers. She regularly moderates and hosts panel sessions, webinars, and conferences on nuclear energy and actively participates in the societal conversation on the potential of nuclear energy as a climate change mitigator. Sannah is co-founder and director of The Empowered Atom – an editorial knowledge platform that attempts science communication through art and design.

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Declaration Form

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Number of words of submission: 4640

I am a candidate for the degree: PhD Nuclear Energy Futures

Academic Institution/Department: Engineering Department, University of Cambridge

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Rethinking low-level radiation risks

The Linear Non-Threshold (LNT) Model for radiation and its scientific validity.

Cambridge - McKinsey Risk Prize Submission
Submitted: April 2, 2023
Sannah H.P. van Balen

1 Introduction

Radiation is impossible to sense; it doesn't have a smell, a taste, a sound, a texture, or a characterizing appearance. Nevertheless, high-level radiation (HLR) can damage our bodies and result in serious health effects (e.g. Acute Radiation Sickness (ARS)). In cases of low-level radiation (LLR) exposure, the health risks are more difficult to pinpoint. These primarily actualise as an increased probability of developing cancer (known as stochastic effects). In radiation protection, the linear non-threshold (LNT) model is used to determine dose limits and protect people from the potential harmful effects of radiation [1].

The validity of the LNT model is a current topic of controversy. Questions surrounding its applicability arise as scientists, policymakers, and regulators attempt to understand and learn from the dense collection of data gathered over the past decades. Although this data has proven to be consistent with the LNT model, the data also fits well with other alternatives [5]. For example, the findings also agree with threshold models and even those predicting hormesis (radiation-induced homeostasis). The latter indicates the potential for radiation to improve our health instead of harm it. As the most influential theory in radiation protection, the LNT model underpins existing nuclear safety regulations and safety culture [1]. A shift away from LNT would drastically change the way the nuclear sector performs safety.

In light of these new scientific developments, this essay re-evaluates traditional risk assessment related to LLR. The first section introduces the field of radiation protection and how radiation safety standards are developed. It outlines the LNT model and the principles that serve as the foundation for traditional risk assessment. The second section discusses the scientific validity of the LNT model considering new health science data and insights surrounding LLR. This is followed by an exploration of the ramifications of traditional risk assessment, with a focus on radiophobia. Finally, this essay reflects on potential ways forward and argues for a contextual approach at the low-dose region that emphasises the need for dose justification rather than limitation.

2 Radiation and Radiation Safety

Perhaps surprisingly, we are surrounded by radiation all the time - see Table 1 for common scenarios of exposure. We ourselves are even a little radioactive and irradiate others with our presence [3]. Depending on the source and isotope, different types of radiation are emitted that affect the body differently. You might remember from physics classes in high school that alpha, beta, and gamma radiation each have their own characteristics. For example, gamma radiation can travel through many materials and is harmful from the outside while alpha radiation must be ingested or inhaled to have an effect.

2.1 Measuring Low-level Radiation

Three concepts are commonly used:

- The absorbed dose (unit Gray) describes the amount of energy deposited in tissue.
- The equivalent dose (unit Sievert) considers the different types of radiation (alpha, beta, gamma) by adding a weighting factor.
- The effective dose (unit Sievert) additionally considers the sensitivity of different tissues by adding a second weighting factor.

Measuring and describing radiation is an important step in radiation protection. The most commonly used value is the effective dose as it allows different scenarios of radiation exposure to be compared. It is important to note that the effective dose is an artificial quantity with no *physical* significance. Its sole purpose is to sum different types of radiations and their effects on the body to create a *unifying* unit of radiation risk [5]. Consequently, two scenarios described using the same effec-

Table 1: Common scenarios of radiation exposure [2, 3, 4].

Scenario	Dose [mSv]
Average natural background radiation over a year	2.4
Radiation from eating food, drinking water, and breathing air over a year	0.4
Radiation from sleeping next to someone every night for a year	0.01
Radiation from taking a transatlantic flight	0.08

tive dose can lead to widely different health impacts. For example, at an acute high exposure of 5000 mSv we expect half the people exposed to die [4], yet 50,000 mSv (ten times the effective dose), given in multiple smaller doses and targeted to a specific area of the body, can be given in a course of radiotherapy for breast cancer patients [6].

2.2 Assessing low-level radiation risks

After the quantification of radiation into dose, the next step is to translate radiation dose into health risk. There are two categories of health effects related to radiation exposure: harmful tissue effects (cell death) and stochastic effects (cell modification). At LLR exposure, we are only concerned with the latter as radiation-induced cell death requires higher levels of dose [5]. The risks related to LLR come in the form of cell modification and actualise in a higher probability of getting cancer.

Translating dose to health risk is performed through the dose-response relationship. It is currently assumed that this relationship is **linear** and **without** a radiation threshold above which health effects happen [1]. This descriptive risk model, commonly referred to as the Linear Non-Threshold (LNT) model, prescribes current radiation protection principles and provides the basis for the nuclear safety regime as we know it. Figure 1 illustrates the LNT risk model and its assumptions [1].

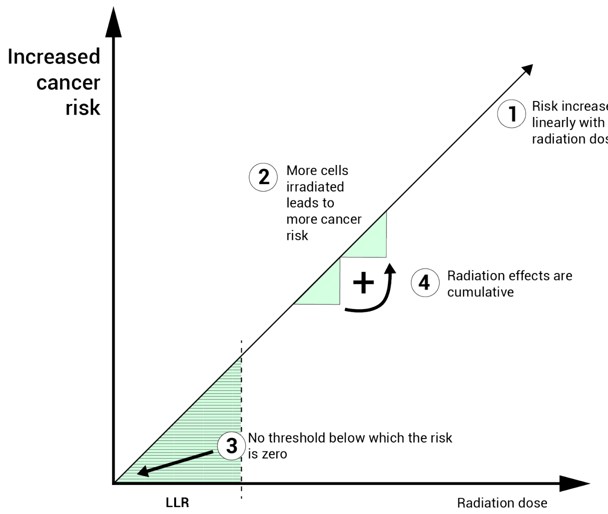

Figure 1: LNT Model and its assumptions [1]. Illustration by Lucy Henshall [7].

The first assumption is that the risk of radiation-induced cancer increases **linearly** with increasing radiation dose [1]. More specifically, the risk of radiation-induced cancer is **proportional** to the number of cells in the body that are irradiated (second assumption). This means that the more cells that are exposed to radiation, the higher the risk of cancer. Thirdly, the LNT model assumes that there is **no threshold** below which radiation exposure is safe. This means no matter how small the dose, each exposure carries *some* risk of causing cancer. And finally, the effects of radiation exposure are assumed to be **cumulative** over a person's lifetime. This means that an individual exposed to low levels of radiation over a long period of time, carries the same risk of cancer as an individual exposed to a higher level of radiation in a shorter period. An additional important characteristic of the LNT model is that it does not make any assumptions about the individual characteristics of the person exposed [5]. On the contrary, the model assumes that the risk of radiation-induced cancer is *solely* proportional to the radiation dose received and the same for all individuals regardless of age, sex, or health status.

2.3 Regulating low-level radiation

Now that there is a framework to assess radiation risks, the final step is to set regulations for radiation protection. The International Commission on Radiological Protection (ICRP) plays an important role in radiation protection. In its own words, the ICRP is "an independent, international organization that advances for the public benefit the science of radiological protection, in particular by providing recommendations and guidance on all aspects of protection against ionizing radiation" [8]. More than 30 countries participate in its activities by assigning experts knowledgeable in the science and policy related to radiological protection. The product of the ICRP's activities is a database of reports with recommendations for radiation risk assessment and management that turn into (nationally determined) radiation codes and standards.

The mission of the ICRP is to "contribute to an appropriate level of protection for people and the environment *without duly limiting* the desirable human activities that may be associated with radiation exposure" [1]. To realise this mission, the ICRP developed three principles that govern the system of radiological protection: justification, optimization, and limitation. Justification implies that any excess radiation exposure should *do more good than harm.* For example, high levels of radiation to treat cancer are acceptable as the alternative is more harmful. The optimization principle, commonly referred to as ALARA, dictates that radiation should be kept As Low As Reasonably Achievable, taking into account economic and societal factors. This is a particularly powerful principle to the nuclear safety culture; it defines an attitude to safety that is based on constant improvement. The difficulty lies in determining how far to take this given economic and societal costs (that are often more difficult to estimate). And finally, the limitation principle refers to dose limits that must be set to protect people from the harmful effects of radiation (see Table 2).

3 What does the data tell us?

While the LNT model has been used for decades to guide radiation safety regulations and standards, it has been subject to criticism. Questions surrounding the scientific validity of LNT arise as scientists and policymakers attempt to understand and learn from the dense collection of data gathered over the past decades. This section considers the latest epidemiological evidence and biological knowledge on radiation health effects. It reflects on what the data can tell us, what it fails to provide certainty on, and what these findings can tell us about the cogency of the LNT model.

Much of the data considered here was gathered and interpreted with the help of Prof. Gerry Thomas OBE, a renowned expert in Molecular Pathology. Throughout her career, Prof. Thomas took a leading role in understanding radiation health effects, particularly those resulting from the Chernobyl and Fukushima nuclear accidents. She is founder and director of the Chernobyl Tissue Bank (CTB), established to collect, document, store and issue biological samples [9]. She also regularly acts as a science communicator to publics, including the most affected communities around Chernobyl and Fukushima.

In 2017, Prof. Thomas was asked by the Oxford Martin School to contribute to a Restatement on the health effects of low-level ionizing radiation [5]. The Restatement reviews the natural science evidence base underlying areas of current policy concern and controversy [5]. The aim of this report is to facilitate decision-making on what is deemed *acceptable exposure* – an aim that highlights the appositeness to review the assumptions of LNT underpinning traditional radiation protection. Many important conclusions presented here originate from the Restatement and are evaluated through their bearing on the LNT model.

3.1 Population Studies

Much of what we know about radiation health effects originates from epidemiological data; this is data on the distribution (frequency, patterns) and determinants (causes, risk factors) of radiation exposure events in specific populations [10].

Figure 2 gives an overview of the conclusions of the most important studies conducted on radiation health effects [5]. A particularly important study to highlight is the Japanese Life Span Study (LSS), which included 86,500 individuals with reliable dose rate estimates [11] The results of the LSS are often considered to be a *gold standard* for studies of radiation exposure and health effects, particularly for studies of LLR exposure [5]. This is because the study is based on a large and well-characterized cohort of survivors, who were exposed to a wide range of doses and dose rates of ionizing radiation. Unsurprisingly, it has played a significant role in the development of the LNT Model. In fact, much of the data from the LSS has been extrapolated to the low-dose region, particularly in the range of natural background radiation levels [personal communication, Prof.

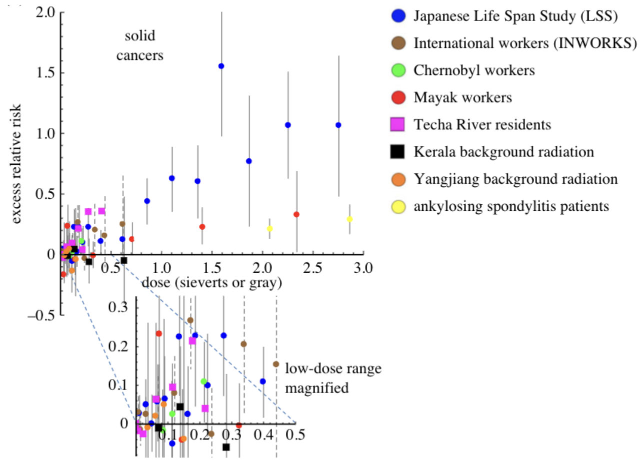

Figure 2: Estimates of excess relative risk of solid cancers from large epidemiological studies. The low-dose region is magnified [5].

Thomas, 2023].

It is clear from Figure 2, that data from the LSS is consistent with a linear relationship with dose. It is all the other studies that show how inconsistent the line provided by the LSS is at lower dose levels. At low dose, the linearity pattern dissipates as data points are scattered around. These results indicate that different dose-response relationships are possible in the LLR region. Indeed, the lowest dose at which an increase in cancer incidence has been observed is 100mSv [5].

There are two conclusions from population studies that are particularly pertinent to the LNT controversy. Firstly, the radiation-induced health effects attributed to the Chernobyl accident tell us something about the importance of *radiosensitivity* in radiation protection. Besides radiation workers who suffered from ARS, the people most impacted by the release at Chernobyl were children; 15 child deaths due to thyroid cancer from 131-I exposure[1] have been attributed to the accident [5]. Prof. Thomas explains that children receive higher doses to the thyroid due to exposure to contaminated milk (children drink more milk than adults) and the fact that their thyroids are still growing. We do not see a similar increase in thyroid cancer in adults following 131-I exposure principally because after the age of around 20, thyroid cells are no longer replicating in sufficient numbers. It exemplifies how the *same* radiation exposure may have a greater impact on some individuals[2] than on others [12]. Individual differences in *radiosensitivity* can thus change the dose-response rela-

[1] The effects on the thyroid are due to 131-I exposure. The thyroid concentrates and stores Iodine, making the dose to this tissue much higher than to other isotopes [personal communication, Prof. Thomas, 2023].

[2] Factors such as genetic predisposition, lifestyle factors, or underlying health conditions may influence individual radiosensitivity [5].

Table 2: Dose limits set by the ICRP [1].

Group	Dose Limit [mSv/yr]
Public	1
Nuclear workers (under 18 yrs)	20

tionship – an aspect that is ignored in the LNT model.

Secondly, epidemiologists have gained great insight into LLR health effects from studying populations living in regions that have particularly high natural background radiation levels [5]. For example, in Kerala (India) the presence of Thorium-containing Monazite sand leads to levels 10-20 times higher than global levels [13]. Another example is Ramsar (Iran), where people are exposed to annual effective dose levels of 260mSv (100 times the global average) [14, 15]. Since these numbers add up to cumulative doses on the order of Sieverts, LNT predicts that these should translate into visible cancers in the population. Surprisingly, there have been no detectable increases in cancer incidence in these populations [5, 15, 16]. This suggests the dose-rate (how much is absorbed in a given time period) rather than the cumulative[3] dose (the sum of radiation) matters in the dose-response relationship. While such null findings cannot tell us much about the true dose-response relationship, they do falsify the fourth assumption of the LNT model.

3.2 In-vitro Studies

A second body of data that speaks to the scientific validity of the LNT model comes from in-vitro studies [5]. These studies are conducted outside of a living organism in controlled laboratory conditions (imagine cells in a Petri dish). Such experimental set-up allows researchers to manipulate and observe cells and tissues and uncover mechanisms of cell-response without needing to consider other complex factors of living organisms. In the case of radiation effects, these studies can provide valuable information about initial cell-damage caused by a predefined radiation dose. Radiation damage occurs primarily in the form of DNA mutations and chromosome aberrations that can result in cancer development. Often, the aim of these studies is to investigate the specific *mechanisms of damage* [5].

Mechanisms of damage describe the steps between radiation impact and cancer development. While it is expected that the initial damage at low dose will result in a linear response, researchers agree that the subsequent steps might not follow the same curve [5]. Processes such as *DNA repair*, *checkpoint arrest* and *non-targeted effects* (genomic instability, bystander effects) may change the dose-response relationship. Some studies[4] even suggest that exposure to low dose and low dose-rate is beneficial to human health – also known as radiation *hormesis*. While much research has been conducted in understanding these pathways better, it remains unclear what the exact steps are and what dose is necessary for radiation-induced cancers to develop [5]. In other words, we cannot derive the dose-response relationship *bottom-up*.

Nevertheless, two conclusions from experimental studies directly question the scientific validity of the LNT model. Firstly, many experimental studies[5] corroborate the importance of the dose-rate on the dose-response relationship. Depending on how quickly an organism is exposed to a total dose (e.g. at once vs. a little over time), the health effect is different. This finding agrees with what we see in population studies, namely that looking at cumulative dose for health risks is not representative of reality. A second collection of studies[6] conducted on animals over a large range of radiation dose witnessed different dose-responses for different cancers. This means that rather than having one single model describing the radiation to risk relation, it is likely that different dose-response relationships exist for different cancers. Modelling a single dose-response relationship for all cancers is thus not possible.

3.3 Unavoidable Uncertainty

The sections above outlined several collections of studies that have proven invaluable in gaining insight into the health-effects of LLR. Researchers have found pertinent new evidence that directly questions the scientific validity of the LNT model and even falsifies its underlying assumptions. Table 3 summarises the counter evidence to the LNT assumptions.

Besides the evidence presented in Table 3 against the LNT model, scientific findings suggest two other fac-

[3] To understand the problem with cumulative dose, consider a shaving cut where you might lose a few ml of blood. Cutting yourself regularly over a lifetime would result in a larger cumulative blood loss. Loosing so much blood in one go would be dangerous, yet in small doses the same amount of blood loss is much less harmful [personal communication, Prof. Thomas, 2023].

[4] See the hormesis database by Calabrese and Blain[17][18]

[5] See an overview by Ruhm et al. [19]

[6] See an overview in the BEIR VII report [20]

Table 3: Summary of LNT assumptions and the counter evidence from population studies and in-vitro experiments.

	LNT Assumptions	Counter Evidence
1	The risk of radiation-induced cancer increases **linearly** with increasing radiation dose.	Population studies show that the linearity pattern dissipates in the low-dose region.
2	The risk of radiation-induced cancer is **proportional** to the number of cells in the body that are irradiated.	Experimental studies show that the initial DNA damage is likely to be proportional to the amount of radiation, but this cannot simply be translated to a proportional risk of developing cancer.
3	There is **no threshold** below which radiation exposure does not increase the probability of cancer.	Population studies, specifically those studying people exposed to high natural background radiation, show no increase in cancer incidence.
4	The effects of radiation exposure are **cumulative** over a person's lifetime.	Both population studies and experimental studies suggest that the rate at which someone is exposed to radiation makes a difference to cancer development.

tors to consider. Namely, the effect of individual radiosensitivity and differences in the dose-response curve for different cancers. The question thus transforms from *is the LNT model still valid?* to *should we even aim to develop one single model?*. Perhaps we need a different model for each type of cancer and have these subsequently edited to suit individual radiosensitivity?

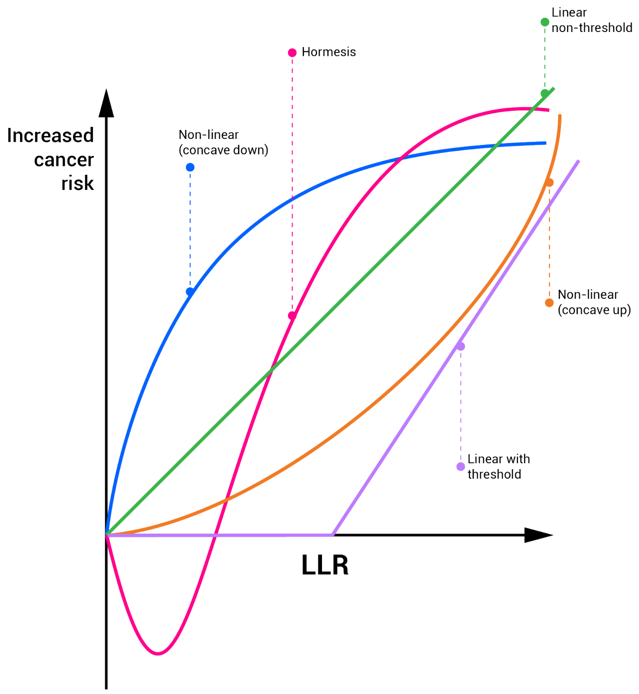

Figure 3: Potential risk models that fit the data at low dose and low dose-rate. Adapted from McLean et al. [5] and illustrated by Lucy Henshall [7].

Before we dive into the search for the most accurate risk model, it is important to remember that the risk uncertainty is mainly located in the low-dose region (around the levels of natural background radiation). There are inherent limits to our ability to describe the dose-response curve accurately that leads to *unavoidable* uncertainty in such models. For example, conducting population studies at such low dose (and thus low risk) would require on the order of a billion people to reach any significant results. Different issues arise with experimental studies. Prof. Gerry Thomas highlights in our personal communication that in-vitro results cannot simply be translated to in-vivo risk conclusions; for one, we do not even know if that single cell tested in-vitro would survive in a human body. On top of that, we cannot replicate *in-vitro* experiments *in-vivo* and expose large numbers of people to radiation without raising serious ethical questions. Though different in nature, these limits mean we cannot replicate the complexity of the dose-response relationship in a living human being. In fact, Figure 3 illustrates the various possible dose-response curves that would match our existing knowledge at low dose and low dose-rate exposures.

4 Impact of Traditional Risk Assessment

New evidence on radiation-induced cancers brings into question the scientific validity of the LNT model. But why does this matter? If anything, it offers a conservative approach to radiation protection and promotes a precautionary attitude towards radiation health risks. Why is conservatism in radiation protection bad? This section explores some of the visible ramifications of the LNT model, many of which resulted from the consequent ALARA culture that developed over the past decades.

One of the most influential aspects of the LNT model is the non-threshold part, which implies that any amount of radiation *no matter how small* will increase the chance of developing cancer [1]. In other words, we assumed that there was no *safe* dose of radiation. Unsurprisingly, and in line with the LNT model, many of us have thus been taught to avoid radiation at all cost and even fear it. This fear, often referred to as *radiophobia*[7], has proven to have deadly consequences.

The deadly effects of radiophobia were particularly visible in the aftermath of the Chernobyl nuclear accident [22]. In the months following the accidents, approximately 115,000 people were evacuated with an additional 220,000 being evacuated at a later stage [23]. Such actions surpassed even the conservatism of the LNT model, as the vast majority did not require evacuation from a radiation protection perspective [23]. In fact, for the most part exposures were only a few times higher than annual levels of background radiation [23]. The psychological impact, though, in the form of social stigma and fatalism on the clean-up workers, resettled families, and parents of exposed children was enormous - resulting in high levels of suicide, alcoholism, and other mental health related effects [24]. Another unexpected ramification became visible in the number of abortions post-Chernobyl. Dr. Robert Gale, called upon by president Gorbachev to treat Chernobyl radiation victims, stated "[w]e estimate incorrect advice from physicians regarding the relationship between maternal radiation exposure from Chernobyl and birth defects resulted in more than one million unnecessary abortions in the Soviet Union and Europe. Ignorance is dangerous." [25]. Although 25 years later, the deadly effects of radiophobia were just as visible in the response to the Fukushima nuclear accident. In fact, although not a single case of cancer has been linked to radiation from the accident, an estimated 2,313 people died from evacuation stress, not having access to medical care, and suicide [26, 22].

The consequences of the LNT model in the form of radiophobia are not only visible during accident scenarios. Many of us will at some point in our lives need nuclear medicine, whether it is for diagnostic purposes (CT-scans/X-Rays) or, in more unfortunate cases, the treatment of cancers. Ironically, the same radiation that

[7]The term radiophobia suggests an irrational fear to radiation, which is a slight misnomer. Considering the misinformation and fear-mongering about radiation, radiophobia should be deemed a very rational response [21].

has the potential to *harm* us through cancer also has the potential to *prevent* and even *cure* cancer. Unfortunately, many people perceive the secondary radiation side-effects as more harmful than the cancer itself. Clinicians have raised the alarm about patients who refuse medical nuclear technologies out of fear of radiation, preventing proper diagnosis and/or treatment [27, 28]. Yet, scaling up the diagnostics field of nuclear medicine is estimated to avert nearly 2.5 million cancer deaths worldwide by 2030 [29]. Using nuclear technology for treatment would bring this number up to 9.55 million prevented cancer deaths [29]. Realigning risk and the perception of risk will be crucial in beating this radiophobia and unlocking the potential of nuclear medicine.

The barriers to the global benefits of nuclear medicine are worsened by a looming global shortage of nuclear medicine produced using radioisotopes that originate from nuclear reactors [30]. Although these reactors are not used to produce electricity, they are subject to a similar level of regulatory scrutiny. The assumptions of LNT have led to demanding nuclear regulations that have slowed down the advancement of nuclear technology and arguably increased radiophobia. In the most basic terms, each nuclear activity must prove itself to be follow the ALARA principle [31]. Although the ICRP emphasises that this principle should consider societal and economic factors, such cost-benefit analysis is rarely conducted. It would certainly be an incredible task to consider all the relevant societal factors and estimate their values; much of these factors can only really be described *post-factum*[8]. Even so, such analyses are vital in understanding risks in their interrelated societal context.

Following nuclear accidents, nuclear regulatory demands generally increased. With a heavy focus on lessons learnt, the nuclear industry set out to ensure such accidents can never happen again [32, 33]. While such ambitions increases the technical safety of nuclear projects, it also confirms thoughts and feelings of radiophobia [34]. *If this much effort goes into mitigating a risk, it must be cataclysmic by nature.* Such thinking has been dominant throughout the past decades as many European countries have divested from nuclear power and planned nuclear phase-outs. Not only did we witness a reduction in the commissioning of new nuclear reactors (Belgium, UK), but several countries decided to abandon their existing nuclear facilities altogether (Austria, Germany). The outcome of these decisions have presented themselves in increased carbon emissions, high energy dependency on questionable regimes, and an unreliable energy supply. All of which have led to suffering - health-wise, financially, and emotionally.

It is dissonant how a risk model created to protect people from the harmful effects of radiation has contributed to much higher orders of harm on a societal scale. Still, the examples above show exactly how LNT assumptions have led to situations where the degree to which the radiation risks are mitigated has affected the ability of the technology to mitigate climate change and improve human well-being. It is time for us to consider such trade-offs, especially when the societal risks are of orders of magnitude higher than the radiation risks.

5 Rethinking Risk Assessment

The evidence presented in the previous sections has put the scientific validity of the LNT model to the test and falsified the main assumptions underpinning the model at LLR regions. However, that doesn't necessarily mean the model carries no value within radiation protection. On the contrary, critics recognise its usefulness as a pragmatic tool in radiation protection that has been instrumental in developing nuclear regulations and protecting people (albeit imperfectly) [35]. It has led to the three useful principles (justification, optimisation, limitation) and resulted in nuclear being the safest source of energy alongside wind and solar [36, 37].

This essay argues that the problematic aspects of LNT have manifested itself primarily in the ambitious concept of ALARA – keeping radiation as low as reasonably achievable. While ALARA promotes a conservative and precautionary approach to the use of radiation, it comes with a heavy regulatory burden. This is especially problematic in LLR exposure where the risk is uncertain and very small. Treating radiation risks like they exist in a silo has led to the current state of affairs, where they are mitigated to such extent that the potential of nuclear technology has dissipated, and the benefits have become invisible. In these situations, the ICRP has failed in its mission to protect from radiation *without unduly limiting* the desirable human activities that utilise radiation [1].

The previous section explored how treating the LNT model as an accurate tool to calculate radiation risks had contributed to harmful decision-making. The question arises what exactly should change to correct the perception gap that has led to such ramifications. There is no straight-forward answer to this. Retiring the LNT model means completely re-writing safety regulations, introducing new principles, new codes and standards, and potentially a replacement model. Society would be confronted with difficult questions such as: Should existing facilities change their radiation protection strategies? and How will we do radiation protection instead? On top of that, the whole nuclear work force will have to be retrained (even re-indoctrinated). Given the misalignment of risk and the perception of risk, many will wonder whether they are being adequately protected from radiation. Whilst keeping the LNT model as a scientific model for the dose-response relationship is not only false but also harmful, erasing it from current practices would result in the collapse of radiation protection as we know it.

This essay recommends limiting the use of the LNT model to higher dose regions (above 100mSv). Whilst initially it was thought to accurately model the dose-response relationship so that risk can be calculated for all exposures, we can no longer in good faith use it to

[8] For example, does the worth of an X-Ray depend on the presence of a positive diagnosis?

calculate risk at low dose and low dose-rate. As such, the LNT model can be solely used as a radiation protection instrument for higher regions of exposure, where health effects have been thoroughly studied and modelled [5]. Through such scoping, we can openly recognise and accept the inherent uncertainty regarding LLR risks without having to discard the valuable benefits of the LNT as a pragmatic tool for radiation protection.

What could be the consequences of such scoping? Accepting the scientific uncertainty of risks at low dose means that *low limits of dose* are meaningless. Firstly, the earlier mentioned dose limits for the population (1mSv/yr) become senseless and can be abandoned. Note that this is the same amount of exposure a person normally living in the UK would get from spending 3 months in Sweden, with naturally higher background radiation [2]. Note also that a whole-body CT-scan breaks this limit by ten times [4]; it is therefore not surprising that patients worry about its safety. Secondly, the performance of ALARA at low dose becomes an idle ambition that comes at large (mental and economic) cost without guaranteed health protection benefits.

Alternatively, the focus could switch from dose *limitation* to dose *justification*. It only makes sense for risk assessment to be contextual, since this is where unexpected ramifications often hide. For example, let us consider Germany's decision to avoid nuclear power to mitigate radiation exposure to the population. Instead, the country decided to open brown coal plants to make up for the reduction in energy production. This has not only resulted in huge greenhouse gas emissions that affect the climate and the air quality, but also increased the radiation exposure to the public – the exact thing they wanted to avoid. Unknowingly to many, coal plants emit more radiation (0.003mSv/yr) than nuclear power plants (0.0009mSv/yr) [3].

It is thus a matter of contextualising a radiation risk in society to accurately depict the intricate scenarios we must choose from. Both at individual and societal level we are constantly confronted with a plethora of complex and interrelated risks to navigate; it becomes a matter of justifying which risks we deem acceptable and which ones we wish to mitigate at what cost.

6 Acknowledgements

I want to thank Professor Gerry Thomas for her time and patience in helping me interpret the science and evidence that has been produced on low-level radiation health effects. Her personal experiences with the Chernobyl and Fukushima communities as well as the various authorities were great motivators for me to write this piece. Another thank you to Lucy Henshall for boosting comprehension through her sleek illustrations. Finally, I want to thank my supervisor Prof. Eugene Shwageraus, Dr. Nathan Read, Nicholas Frayne, and Jamie Edwards for reviewing my work.

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