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Toward a New Paradigm for Risk-Based Radiation Policymaking

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Toward a New Paradigm for Risk-Based Radiation Policymaking

A Dissertation Presented for the
Doctor of Philosophy
Degree
The University of Tennessee, Knoxville

Thomas William Hansen
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DEDICATION

This work is dedicated to my family – my wife Annette, my sons Thomas III and Robert, my daughter Isabella, my mother Sandra, and my father Thomas Sr.

ACKNOWLEDGEMENTS

This work would not be possible except for the support and encouragement received from the faculty, staff, and students of the Department of Public Health at the University of Tennessee, Knoxville. In particular, I am thankful for the expert mentorship offered by the members of my doctoral committee, Drs. Jiangang Chen, Laurence F. Miller, and Robert Nobles. These individuals brought together their experience in environmental health, health physics, and public health policy, respectively, in a manner that benefitted the written products comprising this dissertation. Moreover, I appreciate the support and inspiration provided by my coworkers at Ameriphysics, LLC. Finally, I would like to thank Dr. Cristina S. Barroso for volunteering to serve as both my academic advisor and chair of my doctoral committee. I arrived to the Department somewhat abruptly, and I brought with me nearly 30 years of work experience, certification to the highest level possible within my field, and the stubbornness that one might expect from a person who owns and manages a company he founded. As a result, Dr. Barroso had thrust upon her a somewhat unmalleable advisee. Nonetheless, we enjoyed hours of discussion on the politics and practicality of public health policymaking, and she kept me on a solid path toward achieving whatever goals and objectives were being pursued at the time. I leave the University of Tennessee with an unexpected new world view due in part to the time she has invested in me.

ABSTRACT

OBJECTIVE: An exploratory analysis demonstrating that U.S. radiation policymaking should be remade in a manner that considers the risk tradeoffs associated with dose-limiting regulations.

METHODS: Three studies contribute separate chapters to this manuscript. The first study is a systematic review conforming to PRISMA guidelines. PubMed and the U.S. Nuclear Regulatory Commission's web-based public recordkeeping database were searched for evidence demonstrating a concern for risk tradeoff. The second study conceptualizes a theory based model for predicting risk tradeoff in radiation policymaking. The model integrates sources of risk tradeoff and constructs of moral disengagement theory. The third study reviews radiological data obtained during 11 cyclotron decommissioning projects. The data are translated into meaningful metrics that are valuable for examining risk tradeoffs made by low-level radioactive waste policymaking.

RESULTS: A total of 64 relevant documents were returned by the literature review, but only eight documents were concerned with radiation risks. Only one of the documents reflects an analysis of risk tradeoff, whereas six express a need for forward-thinking policymaking that considers countervailing risks. The result of the second study is an illustrative conceptual model. The model predicts that well-intentioned policymakers, faced with jurisdictional boundaries and other pervasive sources of risk tradeoff, may offer policy solutions that reduce target risks but ignore countervailing risks. Policymaking accomplished in this manner will fail to offer maximum risk protection. Calculated dose equivalents for the 11 sites examined by the third study ranged from 0.01 to 43.2 mSv y^{-1} and correspond to a risk of 0.1 to 432 extra cases of solid cancer or leukemia per 100,000 persons. Waste from nine of the sites exceeds the dose limit specified in the U.S. Nuclear Regulatory Commission’s radiological criteria for unrestricted use. Notwithstanding such findings, cyclotron waste is not regulated as low-level radioactive waste.

CONCLUSIONS: The paradigm for radiation protection policymaking should be remade in a manner that looks beyond the perceived immediate benefits of limiting dose. For a new paradigm to prevail, research that examines risk tradeoffs with a logical framework is needed, and the public must be educated on the unembellished actual risks associated with radiation.

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INTRODUCTION

Background

The term “radiation” is used to describe energy that propagates through space or matter in the form of electromagnetic waves or fast moving particles (Hall and Giaccia 2012). Radiation is characterized as being either ionizing or nonionizing. Ionizing radiation is the subset of all radiation that is energetic enough to create ion pairs by dislodging electrons from an atom and includes x-rays, gamma-rays, neutrons, and charged atomic particles (NAS 2006, Hall and Giaccia 2012). Nonionizing radiation does not have sufficient energy to create ion pairs and includes ultraviolet, visible, and infrared light; microwaves; and radio waves. The radiation paradigm and public health policies this research examine pertain to ionizing radiation, but the term “radiation” will be used throughout. This is consistent with common usage of the term and much of the literature reviewed, including a 2006 report by the National Academy of Sciences that is important to a discussion of the current paradigm. That report defines radiation as “energy emitted in the form of waves or particles by radioactive atoms as a result of radioactive decay or produced by artificial means, such as x-ray generators” (NAS 2006). This definition conspicuously excludes nonionizing radiations.

The world was formally introduced to radiation in 1895 when a German physicist named Wilhelm Roentgen discovered x-rays and their unique ability to pass through the human body and produce radiographic images (Walker 2000). In the first few decades following Roentgen’s discovery, incredible advances were made in the field of medicine and by scientists seeking to harness atomic properties for energy and defense (Walker 2000). Unfortunately, such advances were made in the absence of any policies protecting the health of researchers or their subjects. Early work often assumed that radiation was innocuous, and it was handled with few controls and to the detriment of experimenters' health (Walker 2000, Jones 2005, Colvett 2006). For instance, the x-ray proved to be an effective instrument for probing tissues and materials; however, researchers frequently conducted experiments on themselves and others and in a manner leading to severe overexposures (Walker 2000). Erythema (skin reddening) and burns associated with early research were often dismissed as temporary effects, and it was not until years later that we would learn of radiation's long term consequences.

Within a few decades of its discovery, radiation was known to cause sterility, bone disease, cancer, and other harm (Walker 2000). Notwithstanding the evidence of harmful effects that was accumulating, radiation continued to be used and researched absent of any formal policies or policymaking. Radiation remained a somewhat distal and mysterious phenomenon to much of the public until its harmful effects were demonstrated in spectacular fashion when the U.S. dropped two atomic bombs on Japan in August of 1945 (Holmes 2005, Jordan 2016). Imagery returned from the aftermath in the cities of Hiroshima and Nagasaki suddenly informed the world of insidious harms that could not be forgotten. This would forever change our normative beliefs, and from that point forward it has been impossible to consider any level of radiation aside from its effects.

Features of the Existing Framework for Radiation Policy

Over time, people became as curious about radiation's harmful effects as its other mysterious qualities. As researchers' interests evolved, their findings informed a new field - radiation protection, or what is called health-physics by U.S. practitioners.

Radiation protection policymaking can be traced back to the Second International Congress on Radiology in 1928, where an International X-Ray and Radium Protection Committee was formed from a group of scientists and physicians (Walker 2000, Jones 2005). Its U.S. counterpart, the Advisory Committee on X-Ray and Radium Protection, was formed the following year (Walker 2000, Jones 2005). Both organizations involved themselves in advocacy measures intended to increase awareness and improve handling practices; however, neither group was endowed with statutory authority (Walker 2000).

The framework for U.S. policymaking has evolved considerably over the years. Today, the responsibility for the nation's radiation policymaking is shared by multiple federal agencies: Environmental Protection Agency (EPA), Nuclear Regulatory Commission (NRC), Department of Energy (DOE), Department of Defense (DoD), Department of Health and Human Services (DHHS), Department of Labor (DOL), Federal Emergency Management Agency (FEMA) (EPA 2000). The jurisdictional boundaries of these agencies are not necessarily reflected by mutually exclusive responsibilities, which complicates the rules they publish in the Code of Federal Regulations (CFR). For example, NRC and EPA have overlapping responsibility related to waste from cleanup of radioactive sites. Other significant intersections exist, such as occupational health and safety, transportation, waste disposal, and responsibilities transferred to states. The result is a complex patchwork of regulations that do not seek unified radiation protection and health outcomes.

The Energy Reorganization Act of 1974 transferred certain congressionally mandated responsibilities to the NRC, including an obligation to protect people and the environment from unnecessary exposure to radiation as a result of civilian uses of nuclear materials: nuclear power plants, research reactors, and other medical, industrial, and academic uses (NRC 2015). Moreover, states wishing to regulate certain materials within their borders enter into agreements with the NRC, and in doing so, adopt regulations that do not vary considerably from NRC. Thus, the NRC’s role in radiation policymaking is unique in terms of scope and reach.

A key feature of the regulatory framework used by the NRC is that it authorizes civilian uses of nuclear materials through a process called licensing. The licensed organizations, or “licensees”, then operate nuclear facilities or use or transport nuclear materials according to the NRC’s rules. The rules are published in Title 10 of the CFR (i.e., 10 CFR). The complete set of rules contains 199 parts; however, most of parts apply to rules within the NRC’s jurisdiction but not specifically concerned with controlling radiation.

The NRC’s *Standards for Protection Against Radiation* are specified in 10 CFR § 20 and consist of rules pertaining to general provisions, radiation protection programs, occupational dose limits, radiation dose limits for individual members of the public, radiological criteria for license termination, surveys and monitoring, control of exposure from external sources in restricted areas, respiratory protection and controls to restrict internal exposure in restricted areas, storage and control of licensed material, precautionary procedures, waste disposal, records, reports, exemptions, additional requirements, and enforcement.

The Radiation Paradigm and Risk Tradeoff

The word “paradigm” is used to describe the prevailing group of ideas and theories about how something should be done, made, thought about, or researched (Kuhn

1962). In this regard, and due in part to public concerns and Hollywood embellishments that can be traced back to the 1940s, the radiation protection paradigm is that any amount of radiation is harmful and should be avoided. Policymaking accomplished by the NRC and other actors according to this paradigm results in rigid dose-limiting regulations and, because any dose is presumed harmful, a subsequent requirement is to make every reasonable effort to maintain exposures as far below the dose limits as is practical (NRC 2018a, NRC 2018b). Thus, radiation policymaking is singularly focused on improving health outcomes by lowering radiation dose.

As well-intended as policymaking accomplished according to the radiation paradigm may seem, efforts to reduce one health risk often increases other unmeasured risks. The risks unintentionally or unknowingly fostered are called countervailing risks, and choosing to manage one risk in light of countervailing risks is called a risk tradeoff (Graham and Wiener 1995). Trading one risk for another is a phenomenon encountered in everyday decision-making, and countervailing risks are described by familiar terms such as side effects, collateral damage, and unintentional consequences (Graham and Wiener 1995).

Objectives

The three studies contributing as chapters to this manuscript are related in that they are concerned that U.S. radiation policymaking is not conducted according to a framework that adequately considers risk tradeoff. It is intended that the articles comprising this manuscript will be published in a manner contributing to the literature that federal agencies will look to as they consider the appropriateness of their policies and regulations. Three articles examining three different questions are presented.

Question 1: Is Risk Tradeoff Analysis (RTA) a suitable means of exploring U.S. radiation policymaking decisions? The proposed question is examined with systematic review accomplished according to Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. The study provides a scoping review of the pervasiveness of risk tradeoff concerns in research indexed by PubMed or documents made public by NRC.

Question 2: How is radiation policymaking leading to risk tradeoffs conceptualized with a psychosocial theory-based model? This question is examined by integrating concepts from Moral Disengagement Theory and RTA into an illustrative model that can be used to examine radiation policymaking that is accomplished according to a linear-no-threshold (LNT) model of radiation dose response.

Question 3: Do wastes from cyclotron decommissioning projects pose health disparities that U.S. nuclear waste policies currently ignore? This question is examined with an analysis of data collected during cyclotron decommissioning projects completed by Ameriphysics, LLC. The data reflect radionuclide-specific activity concentrations in concrete. Activity concentrations are transformed to peak dose to a critical group according to federal guidance, wherein the critical group is defined as “the group of individuals reasonably expected to receive the greatest exposure to residual radioactivity for any applicable set of circumstances” (NRC 2006, NRC 2018a). The transformed doses are compared against decommissioning cleanup criterion in 10 CFR 20 and translated into population risk estimates using predictions from the National Research Council of the National Academy of Sciences.

CHAPTER I
RISK TRADEOFF AND RADIATION PROTECTION: A SCOPING REVIEW

A version of this chapter is being prepared for submission to *Environmental Health Perspectives* for consideration.

The student developed the search strategy, selection criteria, and data extraction criteria and drafted the manuscript. The student's Committee reviewed and approved the strategies and criteria developed by the student and read, provided feedback, and approved the final manuscript.

Abstract

OBJECTIVE: To accomplish a systematic review of documents indexed by PubMed and the Nuclear Regulatory Commission public records database to explore the use and suitability of Risk Tradeoff Analysis as a means of informing U.S. radiation policymaking.

METHODS: The aforementioned databases were searched using the inclusionary terms "risk trade", "risk tradeoff", and "risk tradeoffs" and exclusionary terms related to patient choices and preferences and animal predation. Unique documents that were printed in English and concerned with matters of public health were coded according to target risk, constructs of comparative risk assessment, and relevance. Relevance was rated high when constructs of risk tradeoff were discussed in conjunction with radiation risks and low when such constructs were presented in association with other risks. Results are tabulated and followed by a mostly narrative synthesis of findings.

RESULTS: A total of 64 relevant documents were returned by the search, 60 from PubMed and four from Web-based ADAMS. Only eight documents were determined to be highly relevant (i.e., concerned with radiation risks), four from PubMed and four from Web-based ADAMS. Only one of the highly relevant documents reflects an analysis of risk tradeoff, whereas the majority (75%) express a need for forward-thinking policymaking that considers countervailing risks.

CONCLUSIONS: The paradigm for radiation protection policymaking should be remade in a manner that looks beyond the perceived immediate benefits of dose-limiting regulations, and Risk Tradeoff Analysis provides a logical framework that has benefited other public-health related decision making.

Introduction

Radiation exposure is a dreaded environmental hazard, with evidence of public fears tracing back to atomic bombings that occurred in Japan in 1945 and the media reports and Hollywood embellishments that followed (Walker 2000, Jones 2005). The reality of the evidence contemplating radiation's effects on humans, however, is that the risks attributable to low, and in particular, very low, levels of ionizing radiation on humans are unknown (GAO 2000, Tubiana et al. 2009). Epidemiological studies do not have the statistical power needed to describe the dose–response relationship at low doses (Suzuki and Yamashita 2012). Moreover, the actual risk remains unknown in the presence of data from hundreds of thousands of diverse human subjects that have been collected over the better part of a century. That is, the fact that the exact risk remains unknown is not because scientists lack data, but because the preponderance of data suggest that the risk is so small at low doses that it cannot be discriminated.

Due in part to the public's perception of the seriousness of exposure to environmental radiation, policymaking is accomplished according to the paradigm that any amount of radiation is harmful and should be avoided (Cohen 2002, Calabrese 2013, Doss 2013). Because the U.S. framework for policymaking is highly fragmented, multiple federal agencies demonstrate some responsibility for protecting the public from radiation (Levi 1946, U.S. Congress 1946, GAO 2000, GPO 2001). The result is a patchwork of detailed and rigid radiation protection policies that are largely unrelated to each other and do not seek unified health outcomes except to reduce dose to as low a level as reasonably achievable.

An implicit concern of regulatory action is that well-intentioned efforts to reduce one risk may cause other adverse health outcomes (Viscusi 1994, Graham and Wiener 1995). These adverse outcomes are "costs" of the regulatory action. These costs are not exclusively financial; rather, they encompass any type of countervailing risk that arises (Hofstetter et al. 2002). Whenever the portfolio of risk is changed by an action that knowingly or inadvertently generates a countervailing risk (i.e., cost as previous described), a risk tradeoff is said to have occurred (Graham and Wiener 1995).
Thus, policies aimed at reducing dose because any amount of radiation is presumed harmful may unknowingly lead to important risk tradeoffs, especially if the risks due to radiation are lower than predicted or nonexistent as suggested by contemporary critics (Tubiana et al. 2009, Suzuki and Yamashita 2012, Doss 2013). Until the benefits sought by dose-limiting regulations are compared against countervailing risks with a suitable comparative analysis method, we cannot be sure if such policymaking results in optimal health outcomes.

The pool of possible comparative analysis methods is large. Hofstetter et al. examines a variety of popular tools and introduces a subset of methods that provide a means of analyzing risk tradeoffs including life cycle assessment, programmatic comparative risk assessment, benefit-cost analysis, cost-effectiveness analysis, health-

health analysis, comparative risk analysis of alternatives, and risk tradeoff analysis (RTA)(2002). RTA differs from many of the other methods in that it is explicitly proposed as a means of analyzing the effectiveness of decisions designed to reduce risk, and not just the financial costs borne by taxpayers, regulated industries, and consumers to reduce risk (Graham and Wiener 1995). This unique feature of RTA allows decision makers to determine if, at a given financial cost, a policy action optimally minimizes risk (Graham and Wiener 1995). As a mechanism for eliminating policy options that are clearly not to society's benefit, one source claimed that a risk-versus-risk analysis is superior to approaches that rely on cost-effectiveness, particularly in those contexts where there is reluctance to make tradeoffs between monetary costs and health (Viscusi 1994).

Agencies populating the U.S. Executive Branch have been required to weigh the costs and benefits of any regulatory action since February 1981 when President Reagan issued Executive Order 12291 (Presidential Documents 1981, NRC 2017d). That Order was replaced (i.e., revoked) by Executive Order 12866 in September 1993 by President Clinton, but the new Order maintained a requirement to assess all costs and benefits of available regulatory alternatives (Presidential Documents 1993, NRC 2017d). Moreover, the Order compelled federal agencies to "select those approaches that maximize net benefits (including potential economic, environmental, public health and safety, and other advantages; distributive impacts, and equity)" (Presidential Documents 1993). Executive Order 12866 was reaffirmed in January 2011 by President Obama and remains relative today (Presidential Documents 2011).

Due in part to instructions from the Executive Branch, a number of U.S. laws require some form of comparative risk assessment. The 1990 Clean Air Act Amendment requires the Environmental Protection Agency to assess its efforts to reduce risks and report any adverse health or environmental impacts of such actions, including unintended consequences (Rascoff and Revesz 2002). The 1996 amendment to the Safe Drinking Water Act reflects a similar requirement (Rascoff and Revesz 2002). The Office of Management and Budget (OMB), which administers the federal budget and assesses the performance of federal agencies, has used RTA in its analysis of federal agency policymaking. In one instance, OMB even suspended its review of OSHA rulemaking until that agency considered the risk tradeoffs of regulations that would establish permissible exposure levels for more than 600 workplace air contaminants (Rascoff and Revesz 2002).

Despite the availability of comparative risk measures, Executive Orders informing regulatory reviews for nearly four decades, and consideration of risk tradeoff by other agencies, the comprehensive analysis of countervailing risk is not a chief concern of the U.S. federal agency tasked with mitigating radiation-induced detriment in humans, the Nuclear Regulatory Commission (NRC). NRC maintains that as an independent agency, it is not statutorily required to conduct regulatory analysis (NRC 2017d). Instead, NRC "voluntarily complies" with Executive Order 12866 through a set of regulatory analysis guidelines that demonstrate the agency's "desire to meet the spirit of Executive Orders related to cost-benefit reform and decision-making" (NRC 2017d).

The methodology NRC uses for estimating and evaluating the risks and benefits of any decisions conducted under its jurisdiction are described in its regulatory analysis guidelines, but the attributes examined are changes in radiation exposures which are then converted to dollars and summed to obtain the net monetary value (NRC 2017d). The guidelines were originally published in 1983 and are updated from time to time, with the fifth revision being offered as a “draft for comment” in 2017. The draft guidelines remain committed to benefit-cost analysis in dose-converted monetary terms rather than to a strategy for weighing radiation versus other risk(s). A main focus of the guidelines continues to be an emphasis on Probabilistic Risk Assessment (PRA), an analysis tool that examines the monetized population dose that is averted and other economic costs of a decision (NRC 2017d). As evidence of the pervasiveness of PRA in the guidelines, the term is used 44 times in NRC’s explanation of its regulatory analysis.

RTA differs considerably from the methodology presented in the NRC’s guidelines as it consists of identifying risk tradeoffs, weighing the comparative importance of target and countervailing risks, and exploring opportunities to reduce overall risk (Graham and Wiener 1995). Thus, RTA is pragmatic in that it seeks to reduce overall risk rather than trading one kind of risk for another (Graham and Wiener 1995). This study proposes that constructs of RTA are used in a variety of contexts impacting public health outcomes and should be considered similarly suitable for examinations of radiation protections, particularly if NRC intends to meet the spirit of Executive Orders pertaining to regulatory analysis as it claims.

The objective of this study is to systematically review the literature for qualitative evidence that explores the use and suitability of the RTA framework as a means of informing U.S. radiation policymaking. A scoping review conforming to PRISMA

(Preferred Reporting Items for Systematic Reviews and Meta-Analysis) guidelines is intended. To this end, the proposed review will answer the following questions:

1. How frequently is risk tradeoff a primary concern in radiation-related research indexed in PubMed compared to other public health disciplines (i.e., environmental, economic, healthcare, food safety)?
2. How frequently is risk tradeoff a topic of concern in records the U.S. NRC makes available to the public via its web-based database?
3. For documents identified via the searches accomplished to answer questions 1 and 2, how are concepts of risk tradeoff described in association with radiation risk?

Note that although these questions are involved exclusively with concerns of risk tradeoff, this study is not intended to discredit other comparative analysis tools, or even PRA for that matter. Environmental decision-making is generally associated with 10 categorically different types of risk, and no framework ideally covers all risk types (Hofstetter et al. 2002). Moreover, different levels of decision making (i.e., from micro to macro) and dimensions of analysis (i.e., society, environment, and economy) are needed, and some tools perform well for one level or dimension but not the others (Hofstetter et al. 2002). Thus, the goal of this literature review is not to demonstrate that RTA is better than, or a replacement for, other methods of risk analysis as that argument would be moot. Instead, this study hypothesizes that RTA should be part of a holistic approach to maximally optimize net risk reductions.

Methods

Two databases, PubMed and Web-based ADAMS (WBA) were searched according to the process depicted in Figure 1 and explained herein. PubMed is an index

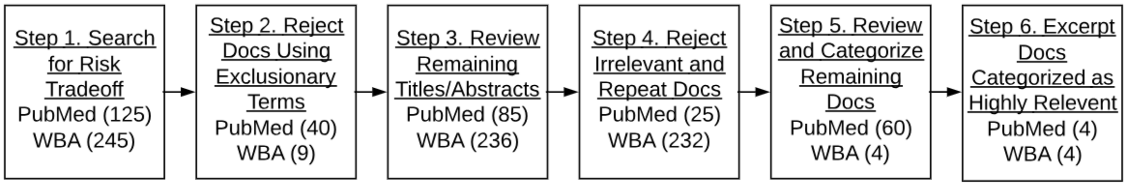

Figure 1. Data Evaluation Process

of more than 28 million citations for biomedical literature from MEDLINE, life science journals, and online books (NCBI 2018). WBA is an interface to the NRC official records repository, the Agencywide Documents Access and Management System (ADAMS) (NRC 2017a). More than 730,000 regulatory guides and reports, inspection reports, NRC documents, correspondence, and other regulatory and technical documents and 2 million bibliographic citations are searchable via WBA (NRC 2017a).

Because it is important to the current study to identify literature wherein risk tradeoff is a major element, a search using variations of the term “risk tradeoff” was conducted with each database. The search terms “risk trade”, “risk trade-”, “risk tradeoff”, and “risk tradeoffs” were used and returned 125 documents in PubMed and 245 documents in WBA. The exclusionary terms “discrete choice experiment”, “patient preference”, “predator”, “predators”, and “predation” were used to narrow the results to 85 and 236 documents, respectively. The searches were conducted on December 7, 2018.

Titles and abstracts of the remaining documents were scrutinized by the principal investigator to determine applicability to the current study. For documents other than journal articles, the respective executive summaries, introductions, and conclusions were reviewed to garner a sense of content. Documents were rejected if they were (1) printed in a language other than English; (2) substantially duplicated in another document, e.g., drafts and reprints; (3) concerned with matters other than public health, e.g., technical criteria for reactor mechanical equipment; or (4) related to the previously described exclusionary terms.

Surviving documents were examined and coded by the principal investigator according to three criteria: (1) target risk, (2) constructs of comparative risk assessment, and (3) relevance to this review. Risks were categorized as (1) radiation, (2) environmental, (3) economic, (4) healthcare, (5) food safety, (6) other, or a combination thereof; constructs were categorized as (1) risk tradeoff, (2) benefit-cost, (3) life cycle impact (4) programmatic risk assessment, or a combination thereof. Relevance is rated (1) high when subject or implied risks included radiation and discussions within the document inferred constructs of risk tradeoff and (2) low when constructs of risk tradeoff are discussed in conjunction with risks other than radiation. These data and the document title, author, and year of publication were transcribed into conventional software (i.e., Microsoft Excel) by the principal investigator. Where the relevance of the source is coded as high, excerpts and major features indicating the manner in which constructs of risk tradeoff were used were also recorded.

Except for counting the number of documents related to each of the risk categories (i.e., radiation, environmental, economic, healthcare, and food safety) to compare radiation risk against other categories, the data are not suitable for quantitative analyses. Instead, a mostly narrative synthesis is used to explore the manner in which risk tradeoffs are described in source documents. Excerpts from documents coded as highly relevant are tabulated along with title, author(s), and year of the document and the name of the database returning the document (i.e., PubMed or WBA). Excerpts are arranged from newest to oldest so that the manner in which references to risk tradeoff have changed over time is observable. Excerpts are followed by a table indicating major features of relevant documents and a narrative synthesis of findings. The narrative is brief because the number of sources is small.

Results

The data collected by the search and relevant to this review (i.e., coded “high” or “low”) are used to populate Table 1 and provide an indication of the use of risk tradeoff in documents available via the two databases. Note that as some documents were concerned with multiple disciplines, it is possible that the document is counted more than once. For this reason, *n* is the total number of documents recovered from each database rather than the summation of disciplines counted.

As the table demonstrates, risk tradeoff is a pervasive feature of public health literature. The benefits of medicines, treatments, and diagnostic methods are carefully compared against risks (Cross et al. 2011, Marchant and Lindor 2012, Brass et al. 2013, Evans et al. 2016, Kim et al. 2017, Guk et al. 2018, Reader et al. 2018). Water and air quality controls are discussed in terms of risks and benefits (Rabinovici et al. 2004, Nevers et al. 2013, Gingerich and Mauter 2017). Risk tradeoffs associated with pesticides, mercury, octane, flame-retardants, mycotoxin, and other chemical and environmental exposures are investigated (Gray and Hammitt 2000, Murphy et al. 2000, Stikkers 2002, Charnley 2003, Wu 2004, van Klaveren and Boon 2009, Shimshack and Ward 2010). Hazardous waste cleanup and transportation, the built environment, recreational promotions, ecosystem management, fish consumption, disinfectants - even helmet laws and the shelf lives of certain foods – are all examined in terms of risk tradeoffs (Hammitt et al. 1999, Breslin et al. 2007, Glickman et al. 2007, de Nazelle et al. 2009, Newbold 2012, Rheinberger and Hammitt 2012, Yang et al. 2012, Crookes et al. 2013, Stern et al. 2014, Guillou et al. 2016).

Table 1. Risk Tradeoff in Primary Sources

Database	n	Public Health Disciplines Represented				
		Radiation	Environmental	Economic	Healthcare	Food Safety
PubMed	60	4	38	1	18	2
WBA	4	4	1	1	0	0

Where the relevance of the primary source is coded as high indicating a relationship to radiation risk, Table 2 provides excerpts demonstrating the implicit manner in which constructs of risk tradeoff analysis are applied, intended, or recommended. The tabulated sources are arranged from newest to oldest.

Finally, Table 3 demonstrates the manner in which concepts of risk tradeoff were used in the eight documents that were found to be highly relevant.

Discussion

Despite considerations of risk tradeoff across an array of topics important to public health, analysis of such tradeoffs is not a pervasive feature of radiation literature as this scoping review located only eight documents that anticipated risk tradeoffs when investigations contemplate radiation risks. Only one document, the 2015 article by Murakami et al., reflects a methodological analysis of risk tradeoff. Overwhelmingly, the majority of documents (75%) generally express a need for forward-looking policymaking that looks beyond the perceived immediate benefits of dose-limiting regulations in a manner that considers countervailing risks (NRC 1985, OMB 2003, Burger et al. 2004, Damon 2006, NRC 2008, Agapova et al. 2017).

Since as early as 1985, NRC has understood that prescriptive policymaking interferes with the commission’s ability to make risk-superior decisions (NRC 1985). Similarly, U.S. Department of Energy (DOE) was warned in 2004 through research it funds that the agency had already spent more than $60 billion on cleanup without realizing a reduction in actual health risk because of the number of ecological, temporal, and human health tradeoffs involved (Burger et al. 2004). Notwithstanding such findings,

Table 2. Key Excerpts from Relevant Primary Sources

Year	Database	Authors	Title/Topic	Excerpts Relative to Risk Tradeoff
2018	PubMed	Murakami M., Kumagai A., Ohtsuru A.	Building Risk Communication Capabilities among Professionals: Seven Essential Characteristics of Risk Communication	1. "[R]isk communication professionals should point out possible risk trade-off problems to support people's decision-making, if they are not aware of them." 2. "To communicate information on risks to people, professionals and authorities need to understand that there is another quality of risk, rather than assuming risk could be adequately assessed with statistical data." 3. "Using a narrative of risk trade-offs..., we introduce the seven essential characteristics required by medical professionals and authorities involved in risk communication."
2017	PubMed	Agapova M., Bresnahan B.W., Linnau K.F., Garrison L.P. Jr, Higashi M., Kessler L., Devine B.	Toward a Framework for Benefit-Risk Assessment in Diagnostic Imaging: Identifying Scenario-Specific Criteria	1. "Diagnostic imaging has many effects and there is no common definition of value in diagnostic radiology. As benefit-risk trade-offs are rarely made explicit, it is not clear which framework is used in clinical guideline development. We describe initial steps toward the creation of a benefit-risk framework for diagnostic radiology."
2015	PubMed	Murakami M., Ono K., Tsubokura M., Nomura S., Oikawa T., Oka T., Kami M., Oki T.	Was the Risk from Nursing-Home Evacuation after the Fukushima Accident Higher than the Radiation Risk?	1. "The most important points are that we need to take evacuation-related risk into account together with radiation exposure risk, and that we need to improve our social system in order to mitigate evacuation-related risks." 2. "[C]ompulsory evacuation needs to be well balanced with the trade-off against radiation risk and in consideration of the concept of acceptable risk. Comprehensive strategies that fully consider both radiation risks and evacuation-related risks will minimize the overall risk to society."
2008	WBA	U.S. NRC	Enclosure 1 - Risk-Informed Decisionmaking for Nuclear Material and Waste	1. Figure 4.1 of the source document conveys a flowchart entitled "Risk Assessment Process". One of the steps is "Assess changes in risk", and in input to that assessment is "competing risks".

Table 2. Continued

Year	Database	Authors	Title/Topic	Excerpts Relative to Risk Tradeoff
			Applications Revision 1.	2. "Understanding the risks and their trade-offs can only enhance the perspective. It is also important to communicate the benefits as well as the risks of a given situation or decision."
2006	WBA	Damon D.R.	A Risk-Benefit-Control Paradigm for Decision-Making	1. "Legitimate activities in society are conducted to produce benefits for the organizations conducting them. However, even a legitimate and beneficial activity may have adverse impacts (risks) as well. In fact, there may be multiple types of both positive and adverse impacts, which differ among different individuals or groups. While it is clear that it is desirable to increase benefits and reduce risks, the fact is that a given action may produce both effects, and may affect different persons differently. Hence, it is desirable to have precision decision-rules and principles in order to choose among alternative actions."
2004	PubMed	Burger J., Powers C., Greenberg M., Gochfeld M.	The Role of Risk and Future Land Use in Cleanup Decisions at the Department of Energy	1. "[L]inking cleanup decisions and goals with the final end state involves a number of risk tradeoffs, including (1) ecological versus human health, (2) worker versus public health, (3) among competing contaminated areas, (4) among temporal patterns of cleanup, (5) among different ecological receptors (plants vs. animals, one animal vs. another), and (6) among the sites across the DOE complex. For the nation, balancing among risks is essential within sites and among Department of Energy sites, as well as among other remediation sites (such as those of Department of Defense and Superfund sites)." 2. "Looking at the current compliance-driven program, the DOE top-to-bottom review team asserted that 'since the program's inception in 1989, more than $60 billion has been spent without a corresponding reduction in actual risk.'"

Table 2. Continued

Year	Database	Authors	Title/Topic	Excerpts Relative to Risk Tradeoff
				3. "There is general agreement that cleanup and remediation of contaminated sites is an important and urgent task. However, there is less consensus concerning the strategy for such cleanup with respect to the role of risk to humans and the environment, and the impact of future land use(s) on cleanup decisions and goals." 4. "[R]isk balancing is required within and among sites for a complex such as the DOE."
2003	WBA	Office of Management and Budget	NRC Pre-Filed Hearing Exhibit NRC000060, Office of Management and Budget Circular A-4, "Regulatory Analysis"	1. “[Policy] analysis should look beyond the direct benefits and direct costs of your rulemaking and consider any important ancillary benefits and countervailing risks. An ancillary benefit is a favorable impact of the rule that is typically unrelated or secondary to the statutory purpose of the rulemaking (e.g., reduced refinery emissions due to more stringent fuel economy standards for light trucks) while a countervailing risk is an adverse economic, health, safety, or environmental consequence that occurs due to a rule and is not already accounted for in the direct cost of the rule (e.g., adverse safety impacts from more stringent fuel-economy standards for light trucks)."
1985	WBA	U.S. NRC	NUREG-1070 "NRC Policy on Future Reactor Designs - Decisions on Severe Accident Issues in Nuclear Power Plant Regulation"	1. "Forward-looking policy needs to be developed in a manner that would encourage innovative ways of achieving superior safety levels at reasonable costs. A highly prescriptive set of technical performance criteria for functions important to severe accident safety would have the effect of preventing the sort of risk-risk tradeoff decisions in plant design that might achieve such optimal results." 2. "The [NRC] staff, in making severe accident decisions, will draw from the research performed under the aegis of the safety goal evaluation program to explore safety-cost tradeoffs within the framework of permissible risk-risk tradeoffs."

Table 3. Major Features of Relevant Documents

Feature	*n*	Document(s)
Presents a quantitative analysis of risk tradeoff	1	Murakami et al. 2015
Conveys a need to improve skills and approaches for communicating risk tradeoffs	1	Murakami et al. 2018
Conveys a need to employ a decision framework for managing risk tradeoffs	6	Agapova et al. 2017, NRC 2008, Damon 2006, Burger et al. 2004, OMB 2003, NRC 1985

no evidence was found indicating that either agency had adapted its rulemaking in a manner to weigh target risk reductions against increases in countervailing risk(s).

Two of the eight “highly relevant” articles returned by the PubMed search reflect lessons learned from the 2011 disaster at the Fukushima Daiichi nuclear power plant. These and other articles examining health outcomes related to evacuation of the Fukushima prefecture make the strongest contemporary case for analyzing risk tradeoffs in radiation policymaking. Impacted areas were evacuated as a means of avoiding radiation exposures of 20 – 100 millisieverts (mSv), an amount commensurate with common medical diagnostic procedures, and such evacuations are known to have resulted in increased mortalities (Murakami et al. 2015). In one study of nursing home residents, the total loss of life expectancy (LLE) due to evacuation-related risks was 11,000 persons-days whereas the total predicted LLE due to the radiation levels involved was several orders of magnitudes less, between 0.11 and 27 persons-days (Murakami et al. 2015). In other research related to Fukushima Daiichi, more than 1,900 deaths were attributed to the physical and mental stresses related to evacuee living by 2015, and five years after the accident, more than 100,000 people were still forced to live in temporary accommodations (Hayakawa 2016). One source states that “[D]isaster-related deaths are undeniably an element of man-made disaster, as these individuals were saved by emergency evacuation and subsequently lost their lives due to insufficient measures to support them (Hayakawa 2016). Furthermore, “Fear of invisible radioactive contamination inactivated [traditional] outdoor activities such as farming, dairy, fishing, gardening, hiking and wild-vegetable/mushroom hunting” and “brought serious social pains although [the radiation] did not acutely hurt our bodies” (Ishikawa 2013). Although the literature is rich with evidence from Fukushima Daiichi substantiating the need to consider the risk tradeoffs associated with managing radiation risks (Murakami et al. 2015, Hayakawa 2016, Murakami et al. 2018), U.S. policymaking remains concerned with keeping radiation exposures as low as possible rather than with utilization of a comparative risk measure such as RTA to reduce overall risk.

Limitations

This review only searches two databases whereas searches via numerous other databases are possible. As a scoping review was intended, this limitation is by design, and PubMed was specifically used because of its popularity among public health researchers and professionals. The other database, WBA, is not a collection of peer-reviewed literature. Rather, it serves as a searchable source of official NRC records including guides, reports, technical documents, correspondence, and other regulatory information written by NRC staff, contractors, licensees, and other agencies or submitted by members of the public (NRC 2017a). In the case of the paper by Dennis Damon, for example, the document reflects the author's submission to the 8th International Conference on Probabilistic Safety Assessment and Management (2006). The paper contains a common disclaimer indicating that it was prepared by an employee of the NRC but does not represent an agreed staff position. Thus, the WBA database represents a powerful tool for searching NRC's official records but not necessarily for discerning scientific consensus. Nonetheless, the documents available via WBA are valuable to the current study because they demonstrate the depth and manner in which risk tradeoffs are considered by the records NRC believes are important enough to share with the public.

By necessity, the search and exclusionary criteria include somewhat generic terms that complicated the review and data reduction. For example, the word “risk” enjoys bountiful use throughout health and policy literature, and just searching this term returns millions of documents. The identification of exclusionary terms was similarly problematic, as few exclusions were possible without rejecting the limited number of papers pertinent to the current study. Searches relying on and complicated by commonplace terms returned a large number documents, making judgement calls on relevance challenging. This is particularly true in the case of documents retrieved via WBA where less than 2% of the 236 documents remaining after exclusions performed by the search engine were found to contain data pertinent to the current study. Nonetheless, the data show that risk tradeoff is considered in a variety of public health contexts but not usually in a manner that informs radiation policy. The fact that the principal investigator was tasked to sort through a large number of documents from WBA was eventually considered to benefit this study as many of the rejected documents demonstrated NRC’s preference to PRA over comparative risk measures.

A limitation of Table 1 and the frequencies contained therein is that the data are not valuable for resolving outright questions of popularity. For example, the PubMed search located 18 healthcare-related items but only four radiation-related articles. Because it is reasonable to expect healthcare-related literature to outnumber what is published concerning environmental radiation, it would be incorrect to conclude from the data that risk tradeoff is a far more popular concern among healthcare researchers than persons interested in radiation risk. Moreover, the data do not show how popular RTA is compared to other common methods of comparative risk assessment such as benefit-cost analysis. This limitation is accepted because questions of popularity are outside the scope of this review.

Conclusion

RTA provides a logical framework for examining risk tradeoffs in radiation protection, and research specifically examining risk tradeoffs relative to radiation policymaking is needed. Nevertheless, strict application of the RTA framework in a manner leading to a meaningful estimate of the net change in health due to radiation rulemaking remains a complicated endeavor. Risk-risk comparisons across a diverse set of health endpoints requires an integrated measure of risk (Gray and Hammitt 2000), and while LLE and Quality-Adjusted Life Years (QALYs) are examples of such measures, neither is currently suitable for aggregating across all health endpoints. Comparing risk versus risk in radiation policymaking is further complicated because the actual effects of low and very low doses of radiation remain unknown.

Nonetheless, research that weighs risk versus risk should not be avoided because of such difficulties. Even when presented with incomplete information, weighing risks according to magnitude, size of impacted population, certainty of estimates, type of adverse outcome, distribution, and timing will move decision-making toward optimization of overall risk (Graham and Wiener 1995). Thus, the paradigm for radiation policymaking should be remade in a manner that relies on a framework such as RTA to consider risk tradeoff.

CHAPTER II

A SOCIAL-COGNITIVE CONCEPTUAL MODEL FOR PREDICTING RISK TRADEOFFS IN RADIATION POLICYMAKING

A version of this chapter is being prepared for submission to *Health Physics* for consideration.

The student developed the methodology, conducted the study, and drafted the manuscript. The student's Committee reviewed and approved the methodology developed by the student and read, provided feedback, and approved the final manuscript.

Abstract

OBJECTIVE: To integrate elements of radiation-dose response, risk tradeoff analysis, and social cognitive theory into a conceptual model that can be used to explore and explain dose-limiting policymaking that occurs as a result of the radiation paradigm.

METHODS: Seminal literature describing risk tradeoff analysis and moral disengagement theory are reviewed. Key constructs from each are presented alongside evidence demonstrating the applicability of such constructs to an investigation of radiation policymaking. A conceptual model is synthesized that demonstrates how the current thinking about radiation is complicated by sources of risk tradeoff and unintended behavior in a manner that leads to policymaking that ignores countervailing (non-radiation) risks.

RESULTS: Sources of risk tradeoff for which evidence is provided include bounded roles, omitted voice, heuristics, old-technology bias, and compensating behavior. Behaviors leading to moral disengagement for which evidence is provided include moral justification, palliative comparison, euphemistic labeling, displacement of responsibility, diffusion of responsibility, minimizing the consequences, dehumanization, attribution of blame, and transformative power of moral disengagement.

CONCLUSIONS: The integrated model predicts that well-intentioned policymakers, informed by the radiation paradigm and facing pervasive sources of risk tradeoff, will offer policy solutions that reduce target risk(s) within the policymaker's jurisdiction and ignore countervailing risk(s) outside of that person's jurisdiction. The net result is policies that fail to offer maximum risk protection, and optimal health outcomes are not achieved.

Introduction

Risk Types and Tradeoffs

Risk is broadly defined as "the chance of an adverse outcome to human health, the quality of life, or the quality of the environment" (Graham and Wiener 1995). Specifically, risks include threats of accidents and illness and to material well-being, happiness, privacy, mobility, and other intangible aspects of health (Graham and Wiener 1995). Risks do not present themselves as outcomes in every individual exposed; rather, the outcomes are observed according to some probability when an entire population is considered. Risk is not explicit to humans, as nonhuman lifeforms can also incur risk and often do when environmental factors are involved (Suter II et al. 1995).

A target risk is the primary focus of a risk-management action (Hofstetter et al. 2002). Conversely, a countervailing risk is the chance of an adverse outcome that presents itself in association with measures aimed at the target risk (Hofstetter et al. 2002). A risk tradeoff occurs when the portfolio of risk is changed by an action that knowingly or inadvertently generates a countervailing risk (Graham and Wiener 1995).

Risk tradeoff is a normal consequence of everyday decision-making. For example, a person at work has weighed the advantages gained from earning that day's wage and other ancillary benefits of employment against the risk of being injured or killed in a traffic accident while commuting to work. Had that person observed degraded traffic conditions due to snow or ice when leaving for work, he or she may have decided to stay home instead. Just as each person weighs risk versus risk numerous times throughout a single day, research examining health and environmental protections demonstrate that risk tradeoff is a pervasive feature of policymaking (Graham and Wiener 1995).

Environmental risk management actions are often investigated in terms of countervailing risks, and examples include examinations of chemicals, cleaners, pesticides, pollution, traffic accidents, foodborne illness, building codes, and accidents at work (Hammitt et al. 1999, Gray and Hammitt 2000, Calandrillo 2001, Kikuchi et al. 2011, Kishimoto 2013). Some of the nation's laws require formal analyses as a means of assessing and resolving risk tradeoffs; for example, the 1990 Clean Air Act Amendment requires the Environmental Protection Agency to assess its efforts to reduce risks and report any health or environmental consequences of such actions (Rascoff and Revesz 2002). Radiation policymaking, however, is accomplished according to the paradigm that any amount of radiation is harmful and should be avoided (GAO 2000, NAS 2006). Policymaking informed by such a paradigm is understood to lead to important ecological, temporal, and human health tradeoffs (Burger et al. 2004).

The Radiation Paradigm

Radiation protection recommendations worldwide, and the policies, regulations, and regulatory guidance borne from these recommendations, are based on a presumed linear-response relationship between radiation dose and cancer risk (Aleta 2009, Doss 2013). The linear dose-response theory was popularized in the mid-20th century and suggests that if a single radiation interaction with DNA, or theoretical “single-hit”, is capable of causing mutagenesis, then more hits would result in proportionally more damage (Cohen 2002, Calabrese 2013, Doss 2013). Since the theory is the extrapolation of a single-hit, all radiation exposure carries some cancer risk, and there is no threshold below which we can consider radiation to be safe (Cohen 2002). Because the theory is primarily characterized by a linear relationship between dose and risk and the absence of a threshold dose, it is commonly referred to as the linear-no-threshold model, or the LNT model.

Due to the reasonably large number of cancers that occur in the absence of radiation, there is no way to precisely determine if a single hit of radiation is what leads to oncogenesis (Tubiana et al. 2009). Radiation epidemiology is further complicated by the fact that radiation from natural sources including the earth’s crust and solar activity bathe us constantly (Tubiana et al. 2009), and it is impossible to discriminate cancers caused by natural radiation from those caused by manmade sources. Consequently, at low doses of radiation we do not have any conclusive scientific evidence correlating dose to adverse health effects (GAO 2000, Tubiana et al. 2009).

The meaningfulness of the previous sentence is lost unless one understands the context in which the term “low dose” is used. According to the National Academy of Sciences committee responsible for reporting the health risks from radiation, a low dose is defined as a dose below 0.1 sievert (Sv) where Sv is a standard international unit of dose equivalence (NAS 2006). While 0.1 Sv is low on the scale of doses received by the cohort from which the Academy substantially bases its findings, atomic bomb survivors, it is far above what a sensible person would consider a low dose. It is about the same dose a person would expect to receive from 10 whole body CT scans; 1,000 chest x-rays; or 10,000 dental x-rays (HPS 2010, NRC 2017b).

There is generally consensus among scientists that cancer risk increases proportionally with acute doses above around 0.1 Sv and protracted doses above around 0.5 Sv (Tubiana et al. 2009, Vaiserman 2010). Consensus wanes at low doses, however, where precise evidence is lacking and the risks may be higher or lower than the linear model or reflect a threshold at which no harmful effects are observed (GAO 2000, Tubiana et al. 2009, Vaiserman 2010). As a result, the LNT model has competed with other models of radiation risk since its inception (Aleta 2009). The alternate models usually considered are a higher risk model, a lower risk model, and a threshold model (GAO 2000). Some of the threshold models even predict a net benefit at lower doses, and the theory that health may be improved by exposures to low levels of radiation is called hormesis (GAO 2000, Vaiserman 2010, Doss 2013).

The reality is that the risks attributable to low levels of radiation on humans are unknown. Epidemiological studies do not have the statistical power needed to describe the dose–response relationship at low doses (Suzuki and Yamashita 2012). Moreover, these risks remain unknown in the presence of data from hundreds of thousands of diverse human subjects that have been collected over the better part of a century. That is, the unknowingness is not because scientists lack data, but because the preponderance of data suggest that the risk is so low that it cannot be discriminated.

Although precise evidence of low dose effects in humans remains elusive, the literature is somehow rich with unyielding support for or against many of the dose-response models. Faced with conflicting scientific opinion, policymakers are left to decide which model of radiation effects best describes the dose-response and serves the public's interest. Due in part to the public's perception of the seriousness of exposure to environmental radiation, U.S. policymaking is accomplished according to a so-called "conservative" approach wherein it is assumed that any amount of radiation causes some harm, and adherence to the LNT model is considered such an approach (NAS 1972, Walker 2000).

The aim of public health is improved health outcomes through evidence-based practices. Thus, the problem with assuming that the current paradigm is conservative is that such a conclusion fails to consider the net effects of radiation policy. That is, if the net effect of presumed conservative policies is poorer health outcomes as a consequence of other exposures, degradation of the environment, or misappropriation of public funds, then such policies fail to serve the public's best interest and should not be deemed conservative. The problem with seemingly conservative models is exacerbated if low levels of radiation are actually harmless or beneficial.

This discussion of the radiation paradigm is not meant to argue for or against any of the radiation dose-response models, and those readers seeking evidence regarding which model is best should look elsewhere. Rather, an overview of the paradigm and criticism is intended as a means of introducing this study aimed at examining the policymaking behaviors exhibited as a consequence of aligning decision-making with the current dose-response model.

Predicting Risk Tradeoffs

In broad terms, the set of tools available for analyzing the risks associated with decision alternatives are called comparative risks analysis (Hofstetter et al. 2002).

Hofstetter et al. examines a variety of environmental assessment tools and introduces a subset of methods that (1) are used in comparative analysis, (2) provide a means of analyzing risk tradeoffs, and (3) have value where decision-support is needed (rather than monitoring-support) (Hofstetter et al. 2002). One of these tools, Risk Tradeoff Analysis (RTA, or risk-risk analysis) is particularly well suited to assess countervailing risks that arise from actions aimed at mitigating target risks (Viscusi 1994, Hofstetter et al. 2002). An advantage of RTA over other methods of comparative risk assessment is that it focuses on the risk effects of a policy rather than tradeoffs between financial costs and health (Viscusi 1994). Where policy options are clearly not benefiting society, RTA may offer greater promise than other approaches (Viscusi 1994).

It is hypothesized that well-intentioned policymakers, informed by the radiation paradigm and facing pervasive sources of risk tradeoff, will offer policy solutions that reduce target risk(s) within the policymaker’s jurisdiction and ignore countervailing risk(s) outside of that person’s jurisdiction. The net result is policies that fail to offer maximum risk protection, and optimal health outcomes are unlikely to be achieved.

Materials and Methods

As a means of providing a simple starting point for the current study, a model illustrating the concept of ideal policymaking is provided by Figure 2. It is a simplification of thinking conveyed by the Health Belief Model, which states in part that the actions a person will take to solve a health problem are influenced by their attitudes and knowledge (Glanz and Rimer 1997, Glanz et al. 2008). Ideally then, well-intentioned policymakers furnished with facts about health outcomes will make decisions that benefit the public.

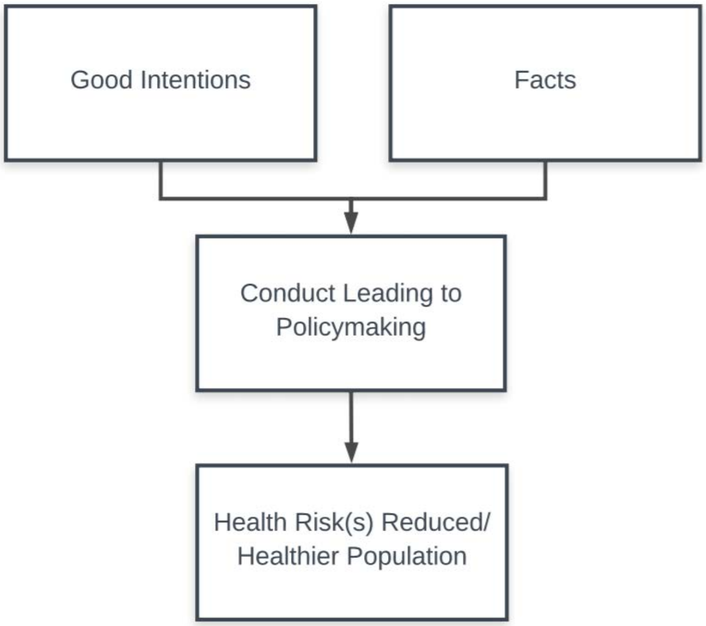

Figure 2. Ideal Policymaking

The research of others demonstrates risk tradeoffs from which we can conclude that radiation policymaking is not accomplished according to the ideal (Burger et al. 2004, Murakami et al. 2015, Hayakawa 2016). If we assume that policymakers' actions are well-intentioned, then the simple model shows that conduct leading to less than ideal health outcomes must be informed by imperfect knowledge rather than a factual understanding of risk. Thus, constructs from RTA and a theory of social cognitive behavior, moral disengagement, are used to estimate an integrated conceptual model capable of predicting risk tradeoffs in radiation policymaking. First, seminal literature describing RTA and moral disengagement theory are reviewed for key constructs, and such constructs are demonstrated to be factors influencing radiation policymaking. Finally, an integrated model is synthesized.

Sources of Risk Tradeoff

The basic decision-making principle of RTA is that when all of the likely consequences of a regulation or management option are assessed in terms of their costs and benefits, an option presenting the lowest overall risk is selected (Hofstetter et al. 2002). RTA is pragmatic in that it is concerned with finding risk superior alternatives that reduce overall risk rather than trading one kind of risk for another (Graham and Wiener 1995). In seeking opportunities for risk superior alternatives, it is important to understand why risk tradeoffs occur, and according to Graham and Weiner, important sources of tradeoffs include bounded roles, omitted voice, heuristics, old-technology bias, and compensating behavior (Graham and Wiener 1995).

Bounded roles are an unfortunate consequence of specialization (Graham and Wiener 1995). Structurally, the agencies responsible for mitigating risk are organized into pools of experts that will accomplish decision-making according to their competencies and sometimes contrary to the expertise of organizations representing other specializations. Countervailing risks are unlikely to respect the functional boundaries used to discriminate agency jurisdictions.

Omitted voice is a concern when affected parties are absent from the decision-making process (Graham and Wiener 1995). Decision makers are less likely to consider countervailing losses and organized interests will enjoy disproportionate influence when impacted constituencies are not participating in the dialogue. All parties impacted by decision-making should have a voice as a matter of practical ethics, and it is important to consider the risks borne by nonhuman life forms, ecosystems, and future generations that are unable to advocate for themselves.

Heuristics are the cognitive tools humans have acquired through evolution to sort through vast amounts of information and expedite their decision-making (Graham and Wiener 1995). The tendency is to focus on immediate concerns, leaving side effects of decisions to be managed later. Via heuristics, recent events or crises are viewed as issues requiring a response, even when the risk from repeat or like occurrences may be very small.

Change is difficult, and existing, off-the-shelf technologies and methods are easier to come by and garner support around. Where decision-making occurs in space supported by influential organizations or industries, it can be difficult to introduce new or competing alternatives. In these instances, *old technology bias* will lead to risk tradeoffs (Graham and Wiener 1995).

Finally, public health interventions are almost always aimed at influencing behavior, and sometimes such influences will lead to unplanned *human behavioral responses* (Graham and Wiener 1995). The target group may not perform the desired behavior, or the desired behavior may lead to other unintended behaviors.

Moral Disengagement Theory

When discussed as a source of risk tradeoff in the usual sense, behavioral responses are the unintended behaviors that negate reductions in the target risk. For example, if helmet laws make motorcyclists feel safer, wearers may be more inclined to operate their vehicles in a manner that is considered unsafe without a helmet. In addition to behavioral responses that are characteristically unplanned, intentional behaviors are also important to a discussion of policymaking conducted according to the radiation paradigm. Such behaviors are examined herein with a popular social cognitive theory, moral disengagement.

According to Bandura's moral disengagement theory, an individual exhibits moral reasoning based on a set of embedded moral standards (2002). This reasoning guides the individual in choosing behaviors that reflect such standards and is ultimately linked to his or her moral action. That is, because people know right from wrong and are intrinsically interested in acting in a moral manner, their behavior is expressed via a self-regulated process that prevents violating a set of personally-held moral standards (Bandura 2002).

Moral disengagement refers to the psycho-social maneuvers that an individual uses on oneself in order to bypass these self-regulating influences (Bandura 2002). Such tricks allow an alternative set of behaviors to be interpreted as not at odds with one’s moral character, including behaviors that would otherwise be deemed reprehensible

(Bandura 2002). Behaviors that arise as a result of suppressing normal morality with moral disengagement include inhumane conduct and various forms of physical, social, and cognitive harm onto others (Bandura 2002). Moral disengagement is characterized by constructs that express the practices one uses to accept destructive behavior.

Moral justification refers to the processes by which harmful conduct is deemed justifiable because it serves a moral purpose (Bandura 2002). By rationalizing the behavior in such a manner, it becomes personally and socially acceptable. Individuals who use moral justification see themselves acting as social or moral agents that are benefiting society (Bandura 2002).

Palliative comparison refers to the cognitive process wherein harmful conduct is justified by comparing it against the unacceptable acts it is meant to contradict, prevent, or eliminate (Bandura 2002). In advantageous comparison, an action that would otherwise be suppressed by moral controls is deemed a righteous retaliatory behavior. An example is one violent act justifying another, or “an eye for an eye” (Bandura 2002).

Euphemistic labeling is accomplished by applying language skills to soften the moral response to harmful conduct (Bandura 2002). It includes sanitizing language; for example, referring to human beings as “targets” or civilian deaths as “collateral damage” in time of war (Bandura 2002). Another euphemistic tool is agentless passive voice, wherein reprehensible conduct appears to be the work of nameless forces or inanimate objects rather than people (Bandura 2002).

In *displacement of responsibility*, an individual minimizes his or her role as an agent in the harm that is caused (Bandura 2002). The individual may cast off any responsibility for the action if it can be attributed to a group decision, even when the harm comes from a group to which they belong (Bandura 2002). Similarly, an individual may claim that they are not responsible for a harmful practice because he or she was not the one who authorized it (Bandura 2002). Displacement of responsibility is likely to occur when regulatory agencies are divided into groups of specialists and each group is assigned to tackle specific risks.

Diffusion of responsibility refers to the mechanism by which personal agency is softened by attributing responsibility to other actors (Bandura 2002). When working in a group, individual tasks may be seen as more moral than the collective effort, making it easier to align oneself with certain tasks (Bandura 2002). Group decision-making also allows individuals to shirk responsibility and blame immoral behavior on others (Bandura 2002).

Minimizing, ignoring, or misconstruing the consequences is used to minimize, disregard, or distort the impact of one's actions (Bandura 2002). Implementation of such practices is easiest in the absence of evidence to the contrary (Bandura 2002). Thus, individuals are less likely to be morally restrained when physical or temporal limitations prevent them from witnessing the harm that their actions cause (Bandura 2002).

Dehumanization is used to turn off empathetic reactions that arise from our morality (Bandura 2002). By stripping away human qualities from people or dividing them into groups that are not like us, it is easier to treat them in a harmful manner (Bandura 2002). Other forms of depersonalization, such as stereotyping and name-calling, are also used to justify immoral action (Bandura 2002).

Attribution of blame allows people to view themselves as victims (Bandura 2002). Consequently, they are driven to behave in a manner that is harmful to others because of perceived compelling circumstances (Bandura 2002). Self-exoneration is realized because the harmful conduct is viewed as a protective response rather than a personal decision that would require moral control (Bandura 2002).

People are not instantly transformed into cruel actors (Bandura 2002). *Transformative power of progressive moral disengagement* is the construct by which small changes contrary to a person's moral compass are achieved (Bandura 2002). By starting with mildly harmful behaviors and slowly progressing to more harmful ones, moral self-restraint is diminished until ruthless acts are possible with little or no remorse (Bandura 2002). Through the transformative power of progressive moral disengagement, inhumane practices become routine (Bandura 2002).

Results

Evidence of Risk Tradeoff and Moral Disengagement

Table 4 provides examples demonstrating sources of risk tradeoff and behaviors of moral disengagement. The examples are not intended to reflect every instance where radiation policymaking is undermined. Rather, the table is expected to validate this study's claim that constructs of the subject theories are germane to the resulting integrated conceptual model.

Integrated Conceptual Model

Figure 3 conveys the model suggested by the current study. A significant departure from the ideal model is the manner in which imperfect knowledge, i.e., the radiation paradigm complicated by sources of risk tradeoff and moral disengagement, is used by policymakers as a suitable approximation of factual risk to enact prescriptive

Table 4. Theoretical Constructs and Examples from Radiation Policymaking

Theory	Construct	Evidence
Risk tradeoff	Bounded roles	• Bounded roles is a prominent feature of the U.S. regulatory framework, with at least the Environmental Protection Agency, Nuclear Regulatory Commission, Department of Energy, Department of Defense, Department of Health and Human Services, Department of Labor, and the Federal Emergency Management Agency all demonstrating some responsibility for radiation policymaking (EPA 2000). • Section 274 of the Atomic Energy Act of 1954 exacerbates the matter of bounded roles because it provides the statutory basis under which the federal government relinquishes portions of its regulatory authority to the states (NRC 2015).
	Omitted voice	• Policies through which cleanup criteria are established are based entirely on reducing radiation-induced risks to a theoretical group of human receptors (NRC 2006), but ignore actual radiation risk to ecological receptors and any non-radiation-induced risks (NRC 2006). • Because U.S. policymaking is accomplished in a framework characterized by bounded roles, groups with similar expertise will hear from the same actors, share similar viewpoints on the seriousness of avoiding the target risk, and collectively disregard countervailing risks (Graham and Wiener 1995). • When efforts are organized in a manner that focuses on a singular risk, as in the case of regulations aimed at reducing radiation-induced effects, omitted voice ensues because the general public is not generally informed enough about the countervailing risks to speak up against them (Graham and Wiener 1995).
	Heuristics	• Decisions to evacuate following the Fukushima Daiichi nuclear disaster areas posing little actual radiation risk resulted in a large number of countervailing evacuation-related deaths (Murakami et al. 2015, Hayakawa 2016). • The incident at Fukushima Daiichi also caused some countries to completely abandon their nuclear energy programs amid concerns over similar radiation releases even though such programs demonstrated impeccable safety records and had supplied clean and reliable energy for decades (Moniz 2011). • Humans innately accomplish relative risk-ranking according to heuristics (Graham and Wiener 1995), and such processes align with the assumption that all radiation is harmful and should be avoided (Walker 2000). • Cancer, DNA lesions, and other mutagenesis are likely to rank higher than other risks, particularly in terms of public perception, but research shows a tremendous gap exists between the public's perception of risk and factual accounts of risk (Tonn et al. 1989, Vassie et al. 2005). In one analysis

Table 4. Continued

Theory	Construct	Evidence
		• of individual risk belief structures, researchers conclude that “the chasm between fact and perception is most notable in the case of nuclear power” (Tonn et al. 1989).
	Old technology bias	• Adherence to “conservative” models of radiation dose response in light of a growing body of evidence from radiation biology indicating the efficacy of cellular repair mechanisms (Tubiana et al. 2009).
	Human behavioral responses	• Nuclear regulations enforce compensating behaviors via a policy of maintaining exposures “as low as (is) reasonably achievable” or ALARA. This policy requires nuclear operators to make every reasonable effort to maintain exposures to ionizing radiation as far below the dose limits as practical, which over time has resulted in acceptance of actions that pile conservatisms on top of other conservatisms (GAO 2000, Walker 2000, Jones 2005).
Moral disengagement	Moral justification	• Rulemaking accomplished according to the radiation paradigm is routinely defended as “conservative” when such policies may not result in an actual reduction in risk (GAO 2000, Burger et al. 2004).
	Palliative comparison	• The target risk of dose-limiting regulations is cancer; thus, it is easy to support compelling actions to the contrary. • Radiation’s effects are often exaggerated (Walker 2000), and actors leveraging such embellishments are likely to accomplish even more advantageous comparisons.
	Euphemistic labeling	• The two major dose limits of the Nuclear Regulatory Commission are its “occupational dose limits” (NRC 2018c) and “dose limits for individual members of the public” (NRC 2018d). The former apply to nuclear workers, and the latter apply to everyone else. This terminology serves to separate workers from the rest of the public. What is not immediately obvious is that working at the occupational limit would put workers at 50 times the risk of developing a solid cancer as would working at the public limit.
	Displacement of responsibility	• Nuclear policymakers are tasked to reduce the risks from radiation hazards, and other agencies are responsible for managing the countervailing risks posed by their decision-making
	Diffusion of responsibility	• In a response to the U.S. Government Accountability Office regarding uncertainties in risk estimates at low doses of radiation, the Environmental Protection Agency claimed “Until the evidence suggests otherwise, EPA is simply following the consensus of scientific organizations in continuing to use the LNT model to estimate risks” (GAO 2000).

Table 4. Continued

Theory	Construct	Evidence
	Minimize, ignore, or disregard consequences	• Nuclear policymakers disregard consequences when they fail to consider the countervailing risks posed by their decisions because of jurisdictional boundaries. • Cleanup of former nuclear sites is associated with important and possibly irreversible ecological risks, and since ecological systems cannot speak for themselves, it is easier to disregard such risks (EPA 1978, Burger et al. 2007).
	Dehumanization	• Regulatory dose limits depend upon whether one is a worker or member of the general public, with the former allowed to received 50 times more dose in any given year than the latter (NRC 2018c, NRC 2018d). Workers may be our friends, neighbors, and family members, but separating them under a worker label makes it easier to accept that that they are due 50 times more risk. When the public is divided into two groups, nuclear workers and everyone else, it becomes easier to garner support for policies that put one group at greater risk than the other.
	Attribution of blame	• Members of the public who live near nuclear power plants or other potential source of environmental radiation may see themselves as victims of big business or uninterested governments (Walker 2000). Consequently, they may put pressures on decision makers to implement increasing restrictive regulations to protect them from radiation, even when such regulations may be transferring risks elsewhere or onto other groups.
	Transformative power of moral disengagement	• Decision makers are practicing transformative power of progressive moral disengagement when they disagree with the premise of the LNT model but support it anyway as mechanism for conservative policymaking because it has worked for them in the past.

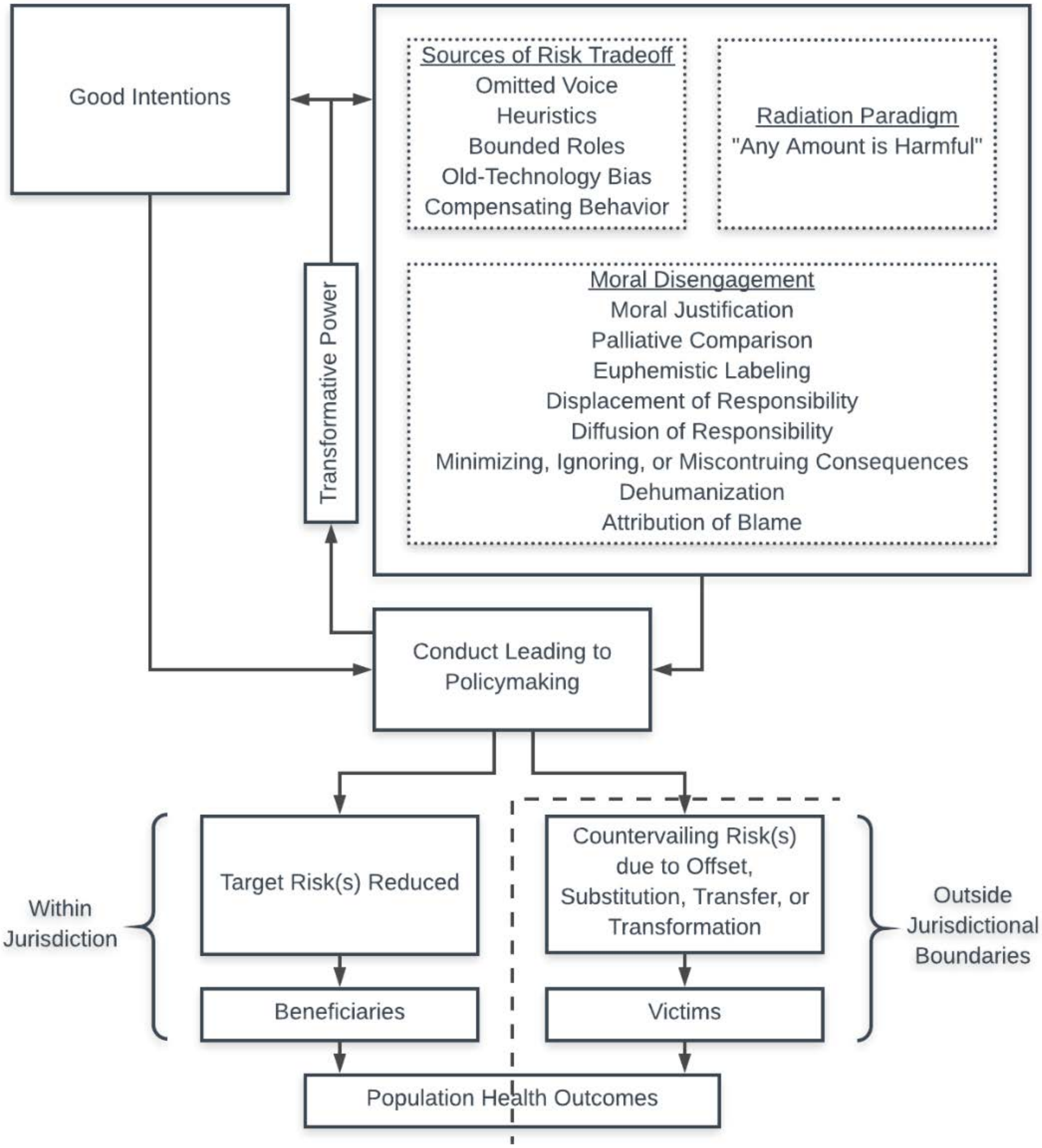

Figure 3. Conceptual Model

dose-limiting regulations. The dotted line in the model represents an impasse defined by jurisdictional boundaries where autonomous action is not practiced to minimize the countervailing risks that arise. The model also suggests that as conduct leading to policymaking is practiced, a transforming effect is observed that makes such conduct easier to repeat. This reciprocal effect is predicted by the construct *transformative power of progressive moral disengagement* that is inherent to Bandura’s theory.

Discussion

The research of others demonstrates that prescriptive policymaking accomplished according to the radiation paradigm leads to risk tradeoffs that offset target risk reductions. For example, in a Department of Energy funded study linking cleanup decisions and risk tradeoffs, Burger et al. cite that in the 12 year period spanning 1989 to 2001, the Department’s own review team had determined that its environmental management program had spent more than $60 billion without a corresponding reduction in actual risk (Burger et al. 2004). In other contemporary research, decisions to evacuate the Japanese prefecture surrounding the 2011 Fukushima Daiichi reactor accident are linked to increased mortality (Murakami et al. 2015, Hayakawa 2016). Evacuations that were undertaken to avoid radiation dose on the order of 0.02 mSv, a level commensurate with routine medical diagnostic procedures, are believed to have caused more than 1,900 deaths from evacuation-related social stresses (Hayakawa 2016). “[D]isaster-related deaths are undeniably an element of man-made disaster”, the authors of one article claim, “as these individuals were saved by emergency evacuation and subsequently lost their lives due to insufficient measures to support them” (Hayakawa 2016). Such outcomes are possible because decision makers have become accustomed to accomplishing radiation policymaking in a manner that ignores countervailing risk. This is the real value of the model predicted by the current study - the evidence-based understanding it provides of the cognitive and behavioral factors that lead policymakers to accept the side effects of their rulemaking.

A key limitation of the current study is that it provides little more than an introduction of risk tradeoff in a radiation-policy context. It is hoped that by demonstrating this model, a case is made for research and subsequent actions that will move the model's dotted boundary down and to the right in a manner that brings countervailing risks into the purview of policymakers. A follow-on analysis of existing dose-limiting regulations with RTA is an opportunity to do so, as the framework RTA reflects is intended to shift the decision paradigm from one that concentrates solely at reducing target risk to one that seeks a reduction across the entire portfolio of risks (Graham and Wiener 1995).

In its consideration of target, countervailing, and coincident risk, RTA seeks to determine the specific set of circumstances representing a "risk protection frontier" at which an increase in protection against one risk means a decrease in protection against the other risk when available interventions are maximally and effectively applied (Graham and Wiener 1995). Along this frontier, risk tradeoff occurs and efforts expended to increase protection against the target risk lead to lesser protection against countervailing risk and vice versa. At the risk protection frontier, maximum risk protection is achieved with the resources at hand, and "risk superior" alternatives that reduce overall risk are needed rather than continued pressures from actions that only trade one risk for another (Graham and Wiener 1995). In application, there may be multiple countervailing risks to consider, so it is useful to consider the risk protection frontier as operating in a numerous directions (Graham and Wiener 1995).

RTA has been used to assess a variety of health and environmental risks (Hammitt et al. 1999, Gray and Hammitt 2000, Calandrillo 2001, Kikuchi et al. 2011, Kishimoto 2013), but in terms of tradeoffs caused by policymaking that protects the public from radioactive hazards, the literature is silent. Instead, contemporary research informing the field of radiation protection seems overwhelmingly set on target-risk reductions and resolving which of the dose-response models best predicts the association between low-level radiation and cancer incidence. Policies that continue to ignore countervailing risks will not achieve maximum protection along the risk protection frontier. Such policies represent a systematic failure to see the “whole patient”, where the term “patient” implies the person, population, ecosystem, or combination thereof impacted by the intervention (Graham and Wiener 1995).

Society agrees to regulations under the premise that such regulations are issued in society's best interest, and where a regulation will do more harm than good, it should not be pursued, irrespective of its benefit to a singular risk and apart from any political motivation (Viscusi 1994). Consequently, research is needed that seeks to determine the net effect of radiation policymaking. For example, research by others connects environmental cleanup activities and risk tradeoffs (Burger et al. 2004, Burger et al. 2007), but the connections are yet to be well quantified due to a lack of comparable risk measures. Risk occurs across a diverse set of health endpoints, and a suitable measure for aggregating across all endpoints is difficult to define (Gray and Hammitt 2000).

Comparing radiation’s risks against other risks is further complicated because the actual effects of low doses of radiation are unknown and may remain so for the foreseeable future. Thus, continued research into risk comparison measures and the effects of low dose radiation are also needed.

Conclusion

Absent a completely factual understanding of the radiation-induced health effects attributable to low-dose radiation, policymakers are left to decide which model of presumed effects best serves the interests of the public. Contemporary policymaking is accomplished according to the paradigm that any amount of radiation dose is harmful, a premise that some claim will lead to risk tradeoffs because it ignores research from radiation biology demonstrating cellular repair and the harmful effects of overregulation. Although risk tradeoff is understood to be a pervasive feature of health and environmental policymaking, the extent to which radiation rulemaking results in countervailing risks is not well researched. It seems clear from at least an exploratory analysis with popular methods of comparative risk assessment and social cognitive theory that radiation policymaking is complicated by certain social and behavioral phenomenon that are known to lead to risk tradeoffs. Because of these findings, research demonstrating the net health effect of radiation rulemaking is needed to determine if a shift in the policymaking paradigm is substantiated. As the integrated model predicted by this study demonstrates, an appropriate paradigm shift would push countervailing risks into the purview of decision makers. Doing so would upset many of the sources of risk tradeoff and lead toward risk-superior rulemaking, even in the face of ongoing uncertainty related to radiation’s low-dose effects.

CHAPTER III

A CRITIQUE OF U.S. LOW-LEVEL RADIOACTIVE WASTE POLICY USING DATA FROM CYCLOTRON DECOMMISSIONING PROJECTS

A version of this chapter is being prepared for submission to *Health Physics* for consideration

The student developed the methodology, conducted the study, and drafted the manuscript. The student’s Committee reviewed and approved the methodology developed by the student and read, provided feedback, and approved the final manuscript.

Abstract

OBJECTIVE: This study makes a case for parity in U.S. radioactive waste policymaking by presenting and interpreting data from cyclotron decommissioning projects.

METHODS: Records from 11 cyclotron sites previously decommissioned provide data conveying the characteristics of residual radioactivity in concrete bioshielding. The dose potential associated with concrete from each site is determined with the RESRAD-BUILD computer code. The resulting doses are (1) compared against the U.S. Nuclear Regulatory Commission’s radiological criteria for unrestricted use and (2) translated into population-risk by applying popular risk estimates from the National Research Council of the National Academy of Sciences. Other data to help frame the concern regarding waste from these projects are presented, including an estimate of the waste volume generated by each site.

RESULTS: Calculated dose equivalents ranged from 0.01 to 43.2 mSv y^{-1} and correspond to a risk of 0.1 to 432 extra cases of solid cancer or leukemia per 100,000 persons. Waste from nine of the sites (82%) exceeds the 0.25 mSv y^{-1} dose limit specified in the U.S. Nuclear Regulatory Commission’s radiological criteria for unrestricted use.

CONCLUSION: According to an international inventory, approximately 350 cyclotrons were believed to be operating worldwide in 2006. These sites do not operate forever, and when they are vacated, decommissioning activities including remediation and demolition are used to make them safe for reuse. These activities generate waste that is not regulated as low-level radioactive waste according to U.S. policy, but would be if generated at a reactor site instead of by a cyclotron.

Introduction

Cyclotrons are particle accelerators; they use electromagnetic forces to propel subatomic particles. The particles are accelerated as a means of achieving a desirable increase in energy, and the energized particles are bombarded against select targets. Desirable nuclear transformations are caused in target materials when the incoming beam of particles, usually protons or deuterons, displaces other subatomic particles. Neutrons that are ejected from incident nuclei go on to cause unintended nuclear transformations in other materials, including those comprising the building structure, the cyclotron, and ancillary support equipment. The materials impinged by neutrons become radioactive in the process. Since the particle beam is not perfectly efficient, any losses (i.e., stray particles) will cause similar transformations and induced radioactivity in whatever adjacent materials are impacted.

Cyclotrons and the facilities in which they are used do not operate indefinitely, and when such facilities are vacated, cleanup activities are accomplished including remediation and demolition. The term “decommissioning” is used to describe these and other activities that are enacted to reduce residual radioactivity and make the site safe for reuse (NRC 2018a). Activities comprising the decommissioning process generate radioactive waste material that the public expects to have managed in its best interest. In a 2018 critique of U.S. nuclear waste policymaking, data were presented to demonstrate the similarities between wastes from one reactor and two cyclotron sites (Hansen 2018). The data in that critique were comprised of radioisotopic activity concentrations in concrete bioshielding, and were used to show how wastes from three sites presenting virtually identical radiological hazards were regulated in a manner leading to very different long-term management solutions. The calculated dose equivalents from residual radioactivity in concrete were 2.75 millisieverts per year (mSv y^{-1}) for the reactor site and 0.778 and 4.91 mSv y^{-1} for the cyclotron sites (Hansen 2018). The corresponding overall risk of solid cancer or leukemia across all three sites was 8 to 50 extra cases per 100,000 persons (Hansen 2018).

Dose calculations in the previous study were based on pathway analysis using the RESRAD-BUILD computer code. The code was developed by Argonne National Laboratory for the U.S. Department of Energy and is specifically designed to analyze human radiation exposures resulting from occupation of radiologically contaminated building (Resrad.evs.anl.gov n.d.). RESRAD-BUILD is additionally approved by the U.S. Nuclear Regulatory Commission (NRC) for use in evaluating contaminated buildings that will be decommissioned and released from regulatory control (Resrad.evs.anl.gov n.d.). The dose outputs from RESRAD-BUILD were translated to risk with estimates published by the National Research Council of the National Academy of Sciences. A limitation of the previous study is that because it was intended to serve as an exploratory analysis, it only examined wastes from two cyclotron sites (Hansen 2018).

Moreover, although the data were assumed to reflect typical activity concentrations, the sites were selected as a matter of convenience rather than according to a specific methodology.

The current study aims to improve upon conclusions from previous research by examining data from 11 cyclotron closeouts accomplished by an NRC-licensed decontamination and decommissioning firm, Ameriphysics, LLC (Ameriphysics). This previously unpublished dataset summarizing Ameriphysics' commercial experience is important as it reflects post shutdown radiological data from a variety of uniquely configured, operated, and located cyclotron facilities.

Radioactive Waste Disposal Regulations

The Energy Reorganization Act of 1974 transferred federal responsibility for regulating commercially generated U.S. radioactive wastes onto the NRC (NRC 2015). How the NRC regulates waste is determined by which of four broad classifications it falls into. Categories include high-level waste, low-level waste, uranium mill tailings, and waste incidental to reprocessing, where the latter refers to certain waste that results from reprocessing spent nuclear fuel (NRC 2017c).

Regulations pertaining to disposal of high-level radioactive waste are found in 10 CFR §§ 60 and 63. These wastes are irradiated reactor fuel, waste resulting from reprocessing irradiated reactor fuel, and other highly radioactive waste that require permanent isolation. These wastes are intended to be disposed in a facility that is part of a geologic repository. In its Nuclear Waste Policy Act of 1982, the U.S. Congress outlined a plan for managing high-level waste (NRC 2015).

Regulations pertaining to the licensing requirements for land disposal of low-level radioactive waste are found in 10 CFR § 61. Low-level waste is radioactive waste that is not classified as high-level waste, transuranic waste, spent nuclear fuel, or certain byproduct materials (NRC 2018g). Disposal of low-level waste occurs at or near the ground's surface. Consequently, these wastes are "classed" according to 10 CFR § 61.55 (NRC 2018h). Class A low-level waste is the most innocuous of the classifications, and it is waste that does not require stabilization or segregation (NRC 2018h). Class B low-level waste presents a greater hazard than Class A and must be structurally stable (NRC 2018h). Class C low-level waste presents a greater hazard than Class B, and requires both structural stability and measures at the disposal facility to protect against inadvertent intrusion (NRC 2018h).

Waste that is greater than Class C is not acceptable for near-surface disposal and must be disposed in a geologic repository designed for high-level waste (NRC 2018h). According to the Nuclear Waste Policy Act of 1982, the U.S. Department of Energy is responsible for siting, constructing, and operating such repositories, and the NRC is responsible approving or disapproving applications to construct, license, and close them (NRC 2015).

Certain byproduct materials are not regulated as either high-level or low-level waste. These materials are defined in 10 CFR § 20.1003 and include mill tailings from uranium or thorium ore, discrete sources of ^{226}Ra, material that has been made radioactive by use of a particle accelerator, and other discrete sources of naturally occurring radioactive material other than source material (NRC 2018a). Disposal of these materials is not regulated except at the state-level and then only when the state chooses to do so.

Cyclotron Waste and Prevailing U.S. Radioactive Waste Policy

According to the definition of waste used throughout the rulemaking promulgated by the NRC, any material that has been made radioactive by use of a particle accelerator is exempted from the regulations pertaining to radioactive waste (NRC 2018a, NRC 2018g, NRC 2018f). Since cyclotrons are particle accelerators, their waste need not be disposed in the same manner as waste generated at reactor facilities, even though such wastes may be indistinguishable in terms of radiological content and corresponding health risk. Meanwhile, according to the rules of other federal agencies, specifically the U.S. Department of Labor (via the Occupational Safety and Health Administration) and the U.S. Department of Transportation, radioactive materials are regulated according to the severity of the hazard they present (Hansen 2018). That is, it seems wastes are regulated by the NRC according to the type of site responsible for generating the hazard, whereas other agencies regulate radioactive material according to its radionuclide-specific concentration and potential for adverse health risk (DOT 2008, DOL 2018a).

According to an inventory published by the International Atomic Energy Agency (IAEA), approximately 350 cyclotrons were believed to be operating worldwide in 2006 (2006a). These sites will eventually close, and with such a large number of closures looming, the value of the current study is that it provides an opportunity to make a mostly prospective examination of the health risks associated with continuing to dispose of cyclotrons according to exiting U.S. policies and resulting regulations.

U.S. radioactive waste policies are public health policies. A principal goal of public health is to seek out and eliminate disparities, or situations where health outcomes are expected to be observed in a greater or lesser extent between populations (Healthypeople.gov 2018). Where some wastes are controlled with regulations in manner that minimizes public exposures and other wastes presenting the same health risk are not, an examination of disparity is warranted.

This study is not a call for more or less regulation; rather, it proposes that U.S. radioactive waste policies intended to benefit the public's health should be risk-based. If cyclotron decommissioning waste presents a risk commensurate with other material classed as low-level radioactive waste, then the same rules for disposal should apply, regardless of whether those rules result in more or less regulation for waste from a specific group of licensees. That is, either stricter rules for cyclotron waste or fewer rules for low-level waste from reactor sites and other material licensees would resolve existing disparities.

Materials and Methods

Description of Data

Ameriphysics has completed 25 projects requiring some form of cyclotron removal, replacement, or dispositioning since the firm's inception in 2008 until the present day. Because these projects were accomplished for purposes other than a critique of U.S. nuclear policymaking, not all of these projects were expected to provide robust quantitative data from which meaningful side-by-side comparisons are possible. Nonetheless, the records from all 25 sites were reviewed and scrutinized, and ultimately, data of sufficient quality was recovered from 11 projects for this study.

Similarly, the nature of the projects conducted by Ameriphysics constrain any robust analysis to investigations of concrete. The rooms in which cyclotrons are housed are constructed of concrete, and these concrete “vaults” serve as bioshields by attenuating the neutron and gamma radiations that are observed during operation. The bioshields are often characterized with robust methods as a means of demonstrating that the area is suitable for some other use or release from radiological control. In such instances, samples of known geometry are collected and controlled in accordance with strict quality procedures. The samples are subsequently prepared and analyzed by an accredited radiochemical laboratory. In contrast, only those concise data necessary to achieve site-specific objectives were usually collected from the radioactive equipment used or kept inside the bioshielding. For example, analogous comparison is sometimes used to estimate the source term of the cyclotron and ancillary support equipment. Although such estimates provide a suitable means for accomplishing site activities related to closeout, they are not sufficiently rigorous for comparative analysis. That is, if the data from one site are used to predict the data from another site in lieu of a separate collection activity, erroneous conclusions are possible.

Certain circumstances related to the collection and analysis of concrete samples remain site specific. Samples from different sites are analyzed by different contract laboratories. Those laboratories sometimes base their analyses on customer-defined libraries, and other times they use their own. Consequently, laboratory reports are rarely identical in terms of the search criteria they reflect. Nonetheless, the data are valuable to a study examining waste policy as they convey principal contaminants, isotopic concentrations, and uncertainty.

Site Specification

The 25 projects reflecting the entire commercial cyclotron experience of Ameriphysics were reviewed for evidence indicating that the scope included activities leading to concrete characterization, remediation, and waste management. In 10 of the 25 cyclotron projects, the situation defining the work was such that bioshielding was not sampled; for example, if the room was to be reused for radioactive material storage, closeout sampling was unnecessary. Concrete characterization data from the remaining 15 projects were examined to determine the representativeness of results. That is, operational concerns sometimes interfere with implementation of an ideal sampling strategy, as in the case of sites where the cyclotron cannot be removed prior to room characterization. In such instances, samples may not be retrieved from beneath or behind the machine where significant neutron activation is possible due to beam losses, and the missing data would potentially lead to lower dose estimates and biased conclusions. Four of the remaining 15 projects were impacted by such concerns of validity, leaving 11 of the originally identified 25 projects to contribute data to the analysis. Thus, in terms of high quality data relevant to the current study, these 11 projects are considered to reflect the entirety of Ameriphysics' cyclotron decommissioning experience (i.e., no high quality cases are omitted).

Data Compilation, Transformation, and Analysis

Data pertinent to the current study – principal contaminants, activity concentration, and uncertainty - are extracted from radiochemical laboratory reports and summarized herein. The laboratory reports are owned by Ameriphysics, but the analyses themselves were carried out by subcontract laboratories. Because of inter- and intralaboratory differences in how the data were reported, the compiled data are not a strict repetition of primary data sources. Rather, the radionuclides detected in any of the samples were listed in the leftmost column, and the resulting matrix of site versus radionuclide was populated with data from the laboratory reports. Consequently, the table demonstrates instances where the radionuclide was not detected (ND) or reported (NR) where the latter reflects missing data. The cyclotron make and model are included atop each column of data, but the site owner and location are intentionally unidentified and remain so throughout this analysis as a measure of confidentiality.

The characterization strategy and therefore the number of samples differed from site to site based on project-specific objectives. As an objective of examining radioisotopic data in this study is to make a decision as to whether residual radioactivity is present in excess of the NRC's radiological criteria for unrestricted use (10 CFR § 20.1402), the sample from each site reflecting the highest cumulative activity is used. The purpose of examining maximum concentrations is not to decide which cyclotron-type poses the most risk as the data are not valuable or comparable in that manner. Rather, the value of the data is that it can be used to decide (1) if cyclotron sites are impacted by the same contaminants, (2) if such contaminants are the same as expected from reactor sites, and (3) if remediation is needed to meet the usual federal regulatory criterion that allows release from radiological controls.

As a means of transforming the data in a manner that benefits a critique of policymaking, the RESRAD-BUILD computer code is used to compute dose equivalent, and the resulting dose is compared against the NRC's cleanup standard and translated to cancer risk using popular estimates published by the National Research Council of the

National Academy of Sciences. Project records were also searched for other data to help frame the concern regarding waste from cyclotron decommissioning projects, including an estimate of the waste volume attributed to each site and factors impacting waste volume.

Results

Concrete Radiological Data

Data from analytical laboratory reports showing residual radioactivity concentration in 5 cm diameter x 15 cm deep (nominal) concrete core samples are used to populate Table 5 for Sites 1 through 11. The data must be considered in context; else, they do not seem to demonstrate that the sites are impacted by the same contaminants. The CS-22 cyclotron operated at Site 4, for example, was shut down in 2000, almost 12 years prior to characterization. Thus, it is reasonable that contaminants exhibiting a half-life of a few years or less have decayed to negligible levels. The characterization sample from Site 10 did not return detectable concentrations of ^{154}Eu, but this contaminant is only expected to be present in small concentrations relative to ^{60}Co and ^{152}Eu, as demonstrated by the other site operating a Siemens Eclipse, Site 2. Finally, ^{55}Fe and ^{3}H were not reported for any except two sites, but that is because the teams characterizing the sites assumed the results would be negligible in terms of dose based on measurements acquired during operation. Given these factors and the relative magnitude of each radionuclide in individual samples, the concrete waste from cyclotron sites is considered to be impacted primarily by long-lived ^{60}Co, ^{152}Eu, and ^{154}Eu.

Table 5. Radiological Data by Facility

Isotope	Activity in Bq g^{-1} (2 Sigma Uncertainty) or ND and MDC Value when < MDC										
Half-Life (ICRP 2008)	Site 1: GE MINItrace	Site 2: Siemens Eclipse	Site 3: IBA Cyclone 30	Site 4: Cyclotron Corp. CS-22	Site 5: GE PETtrace	Site 6: Custom Unit	Site 7: IBA Cyclone 30	Site 8: GE PETtrace	Site 9: GE PETtrace	Site 10: Siemens Eclipse	Site 11: Scanditronix MC-40
^{108m}Ag 418 y	NR	NR	NR	NR	1.70 x 10^{-1} (4.26 x 10^{-2})	NR	ND < 3.16 x 10^{-3}	ND < 7.07 x 10^{-3}	ND < 8.07 x 10^{-3}	ND < 2.27 x 10^{-3}	ND < 3.89 x 10^{-3}
^{109}Cd 461.4 d	NR	NR	NR	NR	6.62 x 10^{-1} (3.44 x 10^{-1})	NR	ND < 8.07 x 10^{-2}	ND < 1.45x 10^{-1}	ND < 1.97 x 10^{-1}	ND < 4.92 x 10^{-2}	ND < 8.99 x 10^{-3}
^{57}Co 271.74 d	NR	6.99 x 10^{-2} (2.21 x 10^{-3})	NR	NR	1.97 x 10^{-1} (1.80 x 10^{-1})	NR	ND < 9.77 x 10^{-3}	ND < 5.18 x 10^{-3}	ND < 2.97 x 10^{-2}	ND < 1.67 x 10^{-3}	ND < 1.39 x 10^{-2}
^{58}Co 70.86 d	ND < 5.85 x 10^{-4}	ND < 3.53 x 10^{-3}	7.15 x 10^{0} (6.14 x 10^{-2})	NR	ND < 6.25 x 10^{-2}	ND < 1.29 x 10^{-2}	ND < 5.00 x 10^{-3}	ND < 1.15 x 10^{-2}	ND < 1.34 x 10^{-2}	ND < 3.66 x 10^{-3}	ND < 6.22 x 10^{-3}
^{60}Co 5.2713 y	5.33 x 10^{-3} (1.24 x 10^{-3})	2.41 x 10^{-1} (5.77 x 10^{-3})	1.04 x 10^{1} (6.11 x 10^{-2})	5.37 x 10^{0} (9.77 x 10^{-3})	7.96 x 10^{0} (6.11 x 10^{-1})	2.00 x 10^{0} (1.90 x 10^{-2})	1.88 x 10^{-1} (7.59 x 10^{-3})	4.48 x 10^{-1} (1.82 x 10^{-2})	6.70 x 10^{-1} (2.15 x 10^{-2})	8.81 x 10^{-2} (5.74 x 10^{-3})	4.51 x 10^{-2} (6.44 x 10^{-3})
^{134}Cs 2.0648 y	ND < 6.92 x 10^{-4}	3.04 x 10^{-2} (4.26 x 10^{-3})	2.29 x 10^{0} (4.55 x 10^{-2})	NR	3.30 x 10^{-1} (4.22 x 10^{-2})	4.07 x 10^{-1} (1.05 x 10^{-2})	1.49 x 10^{-2} (4.81 x 10^{-3})	9.07 x 10^{-2} (1.27 x 10^{-2})	2.48 x 10^{-2} (1.46 x 10^{-2})	1.43 x 10^{-2} (4.74 x 10^{-3})	ND < 6.36 x 10^{-3}
^{152}Eu 13.537 y	8.81 x 10^{-3} (3.81 x 10^{-3})	2.30 x 10^{-1} (9.62 x 10^{-3})	4.74 x 10^{1} (1.86 x 10^{-1})	1.03 x 10^{1} (3.03 x 10^{-1})	8.29 x 10^{0} (5.14 x 10^{-1})	1.84 x 10^{0} (3.33 x 10^{-2})	7.84 x 10^{-1} (2.04 x 10^{-2})	8.55 x 10^{-1} (3.92 x 10^{-2})	3.60 x 10^{0} (6.55 x 10^{-2})	1.61 x 10^{-1} (1.36 x 10^{-2})	6.03 x 10^{-1} (2.81 x 10^{-2})
^{154}Eu 8.593 y	ND < 2.49 x 10^{-3}	3.17 x 10^{-2} (4.44 x 10^{-3})	5.07 x 10^{0} (1.44 x 10^{-1})	7.22 x 10^{-1} (1.34 x 10^{-2})	7.55 x 10^{-1} (9.81 x 10^{-2})	3.81 x 10^{-1} (3.45 x 10^{-2})	8.14 x 10^{-2} (1.16 x 10^{-2})	1.09 x 10^{-1} (2.57 x 10^{-2})	4.40 x 10^{-1} (3.51 x 10^{-2})	ND < 1.30 x 10^{-2}	3.13 x 10^{-2} (1.53 x 10^{-2})
^{155}Eu 4.7611 y	ND < 2.76 x 10^{-3}	NR	1.94 x 10^{-1} (1.09 x 10^{-1})	NR	3.26 x 10^{-1} (7.22 x 10^{-2})	ND < 3.39 x 10^{-2}	ND < 1.22 x 10^{-2}	ND < 2.21 x 10^{-2}	ND < 3.10 x 10^{-2}	ND < 7.18 x 10^{-3}	ND < 1.36 x 10^{-2}
^{55}Fe 2.737 y	NR	NR	NR	NR	NR	NR	2.10 x 10^{0} (3.53 x 10^{-1})	NR	NR	NR	ND < 4.18 x 10^{-1}
^{59}Fe 44.495 d	ND < 1.46 x 10^{-3}	ND < 7.14 x 10^{-3}	3.51 x 10^{-1} (9.69 x 10^{-2})	NR	1.23 x 10^{0} (1.12 x 10^{-1})	ND < 2.68 x 10^{-2}	ND < 9.07 x 10^{-3}	2.12 x 10^{-2} (1.99 x 10^{-2})	ND < 2.28 x 10^{-2}	4.85 x 10^{-2} (1.02 x 10^{-2})	ND < 1.13 x 10^{-2}

Table 5. Continued

Isotope	Activity in Bq g^{-1} (2 Sigma Uncertainty) or ND and MDC Value when < MDC										
Half-Life (ICRP 2008)	Site 1: GE MINItrace	Site 2: Siemens Eclipse	Site 3: IBA Cyclone 30	Site 4: Cyclotron Corp. CS-22	Site 5: GE PETtrace	Site 6: Custom Unit	Site 7: IBA Cyclone 30	Site 8: GE PETtrace	Site 9: GE PETtrace	Site 10: Siemens Eclipse	Site 11: Scanditronix MC-40
^{3}H	NR	NR	NR	NR	NR	NR	8.58 x 10^{-1}	NR	NR	NR	1.92 x 10^{-1}
12.32 y							(2.61 x 10^{-1})				(1.01 x 10^{-1})
^{54}Mn	ND	ND	1.18 x 10^{0}	NR	9.10 x 10^{0}	1.96 x 10^{-1}	1.12 x 10^{-2}	ND	2.19 x 10^{-1}	ND	ND
313.12 d	< 8.99 x 10^{-4}	< 3.52 x 10^{-3}	(5.74 x 10^{-2})		(8.66 x 10^{-1})	(1.20 x 10^{-2})	(4.37 x 10^{-3})	< 1.06 x 10^{-2}	(1.72 x 10^{-2})	< 3.54 x 10^{-3}	< 6.29 x 10^{-3}
^{22}Na	ND	3.53 x10^{-1}	NR	NR	2.75 x 10^{-1}	7.51 x 10^{-1}	2.87 x 10^{-2}	ND	ND	ND	ND
2.6019 y	< 8.44 x 10^{-4}	(3.06 x 10^{-3})			(3.63 x 10^{-2})	(1.75 x 10^{-2})	(4.07 x 10^{-3})	< 1.44 x 10^{-2}	< 2.31 x 10^{-2}	< 2.66 x 10^{-3}	< 8.99 x 10^{-3}
^{95}Nb	NR	NR	2.17 x 10^{-1}	NR	5.96 x 10^{-2}	NR	ND	ND	ND	ND	ND
34.991 d			(5.66 x 10^{-2})		(3.77 x 10^{-2})		< 5.03 x 10^{-3}	< 9.84 x 10^{-3}	< 1.24 x 10^{-2}	< 3.70 x 10^{-3}	< 6.29 x 10^{-3}
^{124}Sb	NR	NR	NR	NR	3.52 x 10^{-1}	NR	ND	ND	ND	ND	ND
60.20 d					(5.29 x 10^{-2})		< 3.04 x 10^{-3}	< 1.22 x 10^{-2}	< 6.07 x 10^{-3}	< 5.66 x 10^{-3}	< 8.84 x 10^{-3}
^{46}Sc	ND	NR	3.03 x 10^{0}	NR	8.29 x 10^{0}	1.62 x 10^{-1}	ND	1.18 x 10^{-1}	4.66 x 10^{-2}	8.95 x 10^{-2}	ND
83.79 d	< 7.70 x 10^{-4}		(1.06 x 10^{-1})		(6.29 x 10^{-1})	(1.44 x 10^{-2})	< 5.00 x 10^{-3}	(1.36 x 10^{-2})	(1.27 x 10^{-2})	(7.07 x 10^{-3})	< 6.29 x 10^{-3}
^{65}Zn	ND	1.01 x 10^{-2}	2.60 x 10^{0}	NR	1.21 x 10^{0}	1.34 x 10^{-1}	ND	ND	ND	3.50 x 10^{-2}	ND
244.06 d	< 1.15 x 10^{-3}	(6.66 x 10^{-3})	(1.91 x 10^{-1})		(1.39 x 10^{-1})	(2.87 x 10^{-2})	< 2.05 x 10^{-2}	< 2.76 x 10^{-2}	< 2.63 x 10^{-2}	(9.07 x 10^{-3})	< 1.41 x 10^{-2}

Dose Equivalence

Residual radioactivity in concrete is transformed to dose equivalent in units of mSv y^{-1} with the RESRAD-BUILD computer code, Version 3.5. The code considers exposures from direct external radiation, inhalation, and incidental ingestion of contaminated dust to determine the radiation dose associated with residual radioactivity in contaminated buildings (Yu et al. 2003, Resrad.evs.anl.gov n.d.). Except for the radionuclides and concentrations from Table 5, the code was operated with its preloaded defaults for all parameters. Thus, the geometry of the source to which the characterization data are applied is assumed to be a concrete volume of 5.4 m^3 (a 36 m^2 circular area x 15 cm deep) with a density of 2.4 g cc^{-1} (Yu et al. 2003). The default model also assumes that the entire radioactive volume erodes at a rate of 2.40×10^{-8} centimeters per day in a manner that, over time, releases 10% of the radioactivity into the air in the respirable particulate range (Yu et al. 2003).

In cases where the data were ND and NR, the corresponding radionuclide is not used as an input to the RESRAD-BUILD model. The output equivalent dose is lower than would be achieved by using reported results, the detection limit when ND, or assuming a value when NR. This is deemed an appropriate data management solution, as the question this study seeks to answer is resolved without presuming the presence of radioactivity. That is, the added dose would only further support conclusions that are already possible whereas the reverse would not necessarily be true.

The dose-outputs of the RESRAD-BUILD code are captured in Table 6. The code will not perform calculations for tritium (^3H) at the same time as other radionuclides. Thus, in the two instances where characterization data included tritium, the code was

Table 6. Site Characteristics

Site	Dose from RESRAD-BUILD (mSv y^{-1})	Dose from ^{60}Co, ^{152}Eu, ^{154}Eu (mSv y^{-1})	Risk relative to unrestricted use criterion	Cancer incidence per 100,000 people	Waste volume (m^3)	Self-shielded	Cyclotron disposed
Site 1: GE MINItrace	1.17×10^{-2}	1.17×10^{-2}	0.05	0.1	0.1	Yes	No
Site 2: Siemens Eclipse	4.89×10^{-1}	4.51×10^{-1}	1.8	4.5	2.2	Yes	No
Site 3: IBA Cyclone 30	4.56×10^{1}	4.32×10^{1}	172.8	432	2257.5	No	Yes
Site 4: Cyclotron Corp. CS-22	1.30×10^{1}	1.30×10^{1}	52.0	130	287.8	No	Yes[1]
Site 5: GE PETtrace	1.63×10^{1}	1.51×10^{1}	60.4	151	149.0	No	Yes
Site 6: Custom 208 MeV	4.91×10^{0}	3.78×10^{0}	15.1	37.8	476.8	No	Yes
Site 7: IBA Cyclone 30	7.78×10^{-1}	7.34×10^{-1}	2.9	7.3	65.6	No	Yes
Site 8: GE PETtrace	1.18×10^{0}	1.11×10^{0}	4.4	11.1	7.5	Yes	No
Site 9: GE PETtrace	3.25E+00	3.16E+00	12.6	31.6	11.6	Yes	Yes[2]
Site 10: Siemens Eclipse	2.18×10^{-1}	2.02×10^{-1}	0.8	2.0	1.7	Yes	No
Site 11: Scanditronix MC-40	4.21×10^{-1}	4.20×10^{-1}	1.7	4.2	48.1	No	Yes

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[1] Cyclotron previously disposed, and volume not captured in estimate.
[2] Cyclotron disposed, but integrated shields shipped to another site for reuse.

operated twice, once with and once without tritium, and the results were summed to determine dose equivalent. To demonstrate that most of the dose is attributable to ^{60}Co, ^{152}Eu, and ^{154}Eu, the code was operated a final time for each site using only those radionuclides. These results, i.e., the site-specific doses from ^{60}Co, ^{152}Eu, and ^{154}Eu, were translated to risk relative to the NRC's radiological criteria for unrestricted use, 0.25 mSv y^{-1}, and to cancer risk using estimates published by the National Academy of Sciences.

Radiological Criteria for Unrestricted Use

Specific controls, such as access restrictions, are used at operating nuclear sites to provide protections against undue risks from radiation and radioactive materials (NRC 2018a). Decommissioning is the formal process to safely remove a site from service and to have such controls lifted (NRC 2018a). At NRC-regulated sites seeking to remove all access restrictions, cleanup is accomplished during decommissioning until the residual radioactivity that is distinguishable from background radiation results in a total effective dose equivalent that does not exceed 0.25 mSv y^{-1} (NRC 2018e). Thus, this criterion for unrestricted use is valuable to the current study in that it provides a numerical basis against which dose outputs from RESRAD-BUILD are compared.

That is, a site demonstrating a dose equivalent of greater than 0.25 mSv y^{-1} above background when its radioisotopic data are transformed with RESRAD-BUILD is expected to undergo remediation that generates waste, and such waste is disposed according to prevailing policy. Moreover, judgments against the unrestricted use criterion allow calculation of meaningful quantitative conclusions. For example, a site demonstrating a total effective dose equivalent of 0.50 mSv y^{-1} is said to be twice the cleanup limit whereas a site demonstrating 0.125 mSv y^{-1} is one-half.

Nine of the 11 site evaluations with RESRAD-BUILD returned results exceeding the NRC’s radiological criteria for unrestricted use and required cleanup before they could be released from radiological control. The calculated dose for concrete from Site 3 is the highest, more than 170 times NRC’s criteria, and the calculated doses for Sites 4, 5, 6, and 9 were more than 10 times the criteria.

Cancer Incidence

Dose-equivalent units are not convenient for communicating health risks to the greater public. Consequently, risk is inferred from a 2006 report entitled *Health Risks from Exposure to Low Levels of Ionizing Radiation, BEIR VII, Phase 2*. This report, commonly called BEIR VII, predicts that on average, one in 100 people would develop a solid cancer or leukemia from a dose of 100 mSv once U.S. sex and age distributions are considered (NAS 2006). As an example of how such translation is valuable, the dose attributed to ^{60}Co, ^{152}Eu, ^{154}Eu in concrete for Site 3, 43.2 mSv y^{-1}, corresponds to 432 extra cases of solid cancers or leukemia per year per 100,000 persons when BEIR VII inferences are used.

Due in part to the speculative nature of the BEIR VII risk estimates, several scientific organizations including the Health Physics Society and the American Association of Physicists in Medicine have warned against multiplying such estimates by large populations to make sensational claims about cancer risks from low doses of radiation (Hendee and O’Connor 2012). The objective of predicting cancer incidence in the current analysis is not sensationalism; rather it is to critique policymaking that is accomplished according to the paradigm such estimates represent. Thus, BEIR VII estimates are used, but their speculative nature is accepted as an important limitation that is discussed in greater detail following a presentation of results.

Other Data

Table 6 is populated with other data that are valuable for understanding each site and factors related to waste management. The total waste volume associated with each project is estimated from transfer paperwork and is provided to convey the magnitude of the policymaking concern such disposal represents. These waste estimates should be considered minimum volumes as shipping records do not account for material that was recycled or disposed via landfills as allowed by regulations that exempt cyclotron wastes. When contemplating the volume of waste these projects generate, it is useful to know that 1 cubic meter of standard concrete weighs approximately 2.7 tons and 1 cubic meter of steel weights approximately 8.7 tons.

Important waste minimizing elements are also recognized. Some sites are configured with integrated shields that lessen neutron-induced radioactivity in structural surfaces in all except the downward vector, and such sites are said to be “self-shielded”. In some instances, cyclotrons are transferred to other sites after shutdown where they can be reused or rummaged for spare parts in lieu of disposal.

Discussion

As the results in Table 6 demonstrate, the concrete bioshielding at all except two sites were impacted by residual radioactivity in concentrations capable of delivering a dose above the NRC’s release criterion. Moreover, much of the dose is attributable to neutron-induced ^{60}Co, ^{152}Eu, and ^{154}Eu. These findings are not unique to cyclotron sites, as reactor bioshielding is also known to contain these principal contaminants in levels sufficient to require remediation (Hansen 2018). In fact, the data reflected throughout Table 5 are so similar to residual radioactivity expected in reactor bioshielding that it is unlikely that even the most experienced health-physicist would be able to determine, explicitly, that the data were obtained from cyclotron sites without the headings and narrative accompanying the table (Hansen 2018).

The fact that the wastes representing irradiated concrete at cyclotron and reactor sites are virtually identical is not a novel concept. Nuclear reactors and cyclotrons are devices that emit neutron radiation as they perform the function for which they were designed, and the process through which neutrons go on to cause other materials to become radioactive is well understood. Induced radioactivity, due to nuclear transformations in the devices themselves, surrounding equipment, and building materials is observed as a function of proximity to the neutron source. The transformed materials are said to become activated, meaning that they are now residually radioactive, and remain so even after the radiation-producing machinery is shut off.

Although the data in Table 5 describe residual radioactivity in bioshielding, the judgment that cyclotrons and reactors produce similar wastes should not be limited to concrete. Induced radioactivity in steel, other metals, water, plastic, wood, drywall, and every other material occurs according to a well understood concept of nuclear and particle physics that is used to express the likelihood of interaction between an incident neutron and a target nucleus, neutron cross section. The standard unit for measuring the cross section is the barn, which is equal to 1×10^{-28} m^2, and the larger the neutron cross section, the more likely a neutron will react with the nucleus. Thus, the extent to which a material is activated is a consequence of its intrinsic isotopic constituency rather than the source of neutrons (i.e., reactor or cyclotron) when the neutron flux and energy are constant.

Critique Using Data from Cyclotron Sites

In review, nuclear fuel and wastes that were generated adjacent to the fuel of a nuclear reactor are managed as high-level waste according to 10 CFR §§ 60 and 63. The remaining wastes from reactor sites are designated as low-level waste, classed as Class A, B, or C, and disposed according to 10 CFR § 61. Cyclotrons are particle accelerators; thus, they need not be classed or disposed as radioactive waste according to the definitions of “waste” and “byproduct material” from 10 CFR § 20.

Notwithstanding such exemptions, the data show that cyclotron decommissioning projects are usually impacted by wastes exceeding the NRC criteria for unrestricted use, and when such sites are remediated, waste exhibiting residual radioactivity is generated. Where concrete is concerned, the long-lived radioactivity in waste is primarily due to ^{60}Co, ^{152}Eu, and ^{154}Eu, but we can infer due to a well-understood concept of physics that other materials will also be radioactive according to an intrinsic characteristic called neutron cross section. The field of physics also tells us that items nearest the neutron flux (i.e., the cyclotron and its targets) are subject to more induced radioactivity than the rest of the site due to the manner in which neutrons are attenuated.

As demonstrated by Table 6 and the accompanying narrative, cyclotron decommissioning projects generate substantial quantities of waste, and the decision-making leading to present regulations appears to have missed such impacts. The facilities at which cyclotrons are used do not operate indefinitely, and eventually, all 350 cyclotrons presumed to be operating by IAEA in 2006 and any new sites will require disposal.

According to a summary of the National Environmental Policy Act of 1969 (NEPA) that NRC publishes on its website on a page dedicated to its governing legislation, every proposal for a major U.S. federal action significantly affecting the quality of the human environment requires a detailed statement on the environmental impact of the proposed action and alternatives (NRC 2018i). NEPA predates the Energy Reorganization Act (1974), the Low-Level Radioactive Waste Policy Amendments Act (1985) and 10 CFR § 20 (1991); nonetheless, rulemaking that exempts cyclotron wastes appears to have circumvented the environmental impact investigation process.

Limitations

This article expands upon previous research in that it examines radiological characterization data from 11 cyclotron sites. These data are valuable for demonstrating the site characteristics encountered by Ameriphysics during execution of its projects, but they should not be used to generalize across all cyclotrons. These data are important, but only represent seven out of the dozens of cyclotron makes and models. Moreover, the experience of a different decommissioning firm could lead to different conclusions. For example, a firm experienced primarily with the GE MINItrace (Site 1) might not conclude that cyclotron sites present a significant hazard, whereas a firm involved only with projects like Sites 3, 4, or 5 may recognize a grave concern.

A site operating one of the cyclotrons for which data is presented should not use the data to predict a source term for their facility. A number of factors besides make and model must be considered when estimating the amount of residual radioactivity impacting a site, including but not limited to site layout, operating history, target configuration, and time since shutdown. Well planned, site-specific characterization remains the best way to determine the nature and extent of induced radioactivity.

The dose calculated by RESRAD-BUILD is only as good as the inputs, and the inputs in this case were limited. A single sample from each site is used to model a concrete volume of 5.4 m^3, and it is possible that this over or underrepresents the actual hazard. The intent of using RESRAD-BUILD to determine dose equivalent is merely to predict dose potential for comparisons against cleanup criterion, not to attribute an absolute dose to each site.

Similarly, risk projections based on the dose model are only as good as the BEIR VII inferences. In all instances, the modeled concrete volume returns doses less than 100 mSv, and as already mentioned elsewhere, it is careless to multiply the risk speculated at low doses by large populations in order to make sensational claims concerning effects. As an example of how the data should not be used, multiplying the incidence forecasted for Site 3 (432 cases per 100,000 persons) by an approximated population of the U.S. (325 million) returns a result of more than 1.4 million excess cancers. The data are not valuable in this manner, and the incidence is calculated and reported only as a means of examining which sites could reasonably be assumed to demonstrate some risk. That is, the risk associated with Site 1 is one in 1 million, and had all sites exhibited a commensurate level of risk, a discussion of waste policy may have been moot.

Conclusion

As demonstrated in Table 6 and the accompanying narrative, cyclotron decommissioning projects have the potential generate substantial quantities of waste exceeding NRC’s dose limits for unrestricted use, and the decision-making leading to present regulations appears to have missed such impacts. The facilities at which cyclotrons are used do not operate indefinitely, and eventually, all 350 or more cyclotrons presumed to be operating in 2006 will require disposal. Several sites have already been decommissioned as indicated by the projects contributing data to this study.

The NRC definition of waste specifically excludes materials produced by particle accelerators; thus, cyclotron wastes are not regulated as low-level waste. If the exemption was removed, such wastes would be classed as Class A and would require disposal at a licensed facility according to 10 CFR § 61. Admittedly, Class A presents the lowest hazard of any of the wastes NRC regulates. Nonetheless, an important conclusion is possible based on this premise: low-level waste policymaking is not accomplished strictly according to risk.

The disparity represented by this policy approach is due to the fact that wastes conveying the same level of induced-cancer risk as materials defined as low-level radioactive waste may be disposed differently or not at all. In turn, populations benefiting from regulated disposal will have their doses controlled whereas populations impacted by unregulated disposals or releases will not. Since radiation-induced cancers are related to dose, not the words bureaucrats use to populate the glossaries that introduce their rulemaking, important risk tradeoffs may be occurring.

Finally, this research is not a call for more or less regulation; rather, it seeks parity. Cyclotron wastes either do or do not present a hazard based upon the radiation dose potential and corresponding risk of cancer incidence demonstrated by this research. If Class A reactor wastes are presumed to present a hazard significant enough to manage, then so should cyclotron wastes presenting commensurate risk(s). On the other hand, if cyclotron waste is decided to be innocuous enough that strict management is not needed, then regulations causing such management of Class A waste from reactors and other nuclear sites should be revisited to verify that they are benefiting the public.

CONCLUSION

Concise Review of Findings

This research is concerned with the risk basis for U.S. radiation policymaking; specifically, that such policymaking is not conducted according to a framework that adequately considers risk tradeoff. Three questions and corresponding studies were proposed and accomplished.

Question 1: Is RTA a suitable means of exploring U.S. radiation policymaking decisions? The literature review returned 64 documents that were concerned with risk tradeoff in some manner, but only 8 documents were concerned with radiation risks. None of the radiation-related documents specifically relied on the RTA framework. Six express a need for forward-thinking policymaking that considers countervailing risks, however, and RTA provides a logical framework that has benefited other public-health related decision making.

Question 2: How is radiation policymaking leading to risk tradeoffs conceptualized with a health-behavior based model? Graham and Weiner propose five prevailing sources of risk tradeoff, and evidence was found linking radiation policymaking to all five. Similarly, policymaking seems impacted by each of the compensating behaviors described by Bandura’s moral disengagement theory. A conceptual model predicts that well-intentioned policymakers, informed by the radiation paradigm and facing pervasive sources of risk tradeoff, will offer policy solutions that reduce target risks within the policymaker’s jurisdiction but ignore the countervailing risks that are presented outside of that person’s jurisdiction. The net result is policies that fail to offer maximum risk protection, and optimal health outcomes are not achieved.

Question 3: Do wastes from cyclotron decommissioning projects pose health disparities that U.S. nuclear waste policies currently ignore? Calculated dose equivalents from the 11 sites examined ranged from 0.01 to 43.2 mSv y^{-1} and correspond to a risk of 0.1 to 432 extra cases of solid cancer or leukemia per 100,000 persons. Waste from nine of the sites exceeds the NRC's criteria for unrestricted use, 0.25 mSv y^{-1}. When these sites are remediated, the resulting waste is not regulated as low-level radioactive waste according to U.S. policy, but would have been if generated at a site other than a cyclotron facility. A case for disparity is identified because populations benefiting from regulated disposal will have their doses controlled whereas populations impacted by unregulated disposals or releases will not.

Limitations

Each of the studies was impacted by a unique set of limitations. As those article-specific limitations are sufficiently examined in the discussion sections of respective chapters, there is no value in restating them here.

A key limitation of the overall research effort reflected by the compiled works is that this is exploratory work at best. As demonstrated by the systematic review, this research did not identify a single study wherein the formal framework suggested by Graham and Wiener was used to analyze risk tradeoffs when radiation was a concern. Moreover, none of the articles presented herein convey a formal analysis according to such a framework. Nonetheless, an exploratory analysis was the goal, and this research is considered important because it shows (1) risk tradeoffs are likely occurring, (2) an evidence-based framework exists to assess such tradeoffs, and (3) radiation researchers and policymakers are not currently relying on this framework.

Another limitation is that in making a case for a new paradigm for policymaking, this research does not present any new finding that are valuable for determining which model of dose-response best predicts the association between radiation dose and adverse health effects. This limitation is by design, as the controversy surrounding such models is expected to continue for some time. What this research demonstrates is the manner in which policymaking can be improved by examining the circumstances leading to risk tradeoffs, regardless of which model of dose-response prevails.

Recommendations for Future Research

The fundamental recommendation of this work is that in order for a new policymaking paradigm to be made, analyses that specifically examine the countervailing risks posed by dose-limiting regulations are needed. Such examinations should weigh the benefits of radiation dose risk reductions against costs due to countervailing risk according to (1) magnitude of risk, (2) size of population impacted, (3) certainty of risk estimates, (4) type of adverse outcome, (5) distribution, and (6) timing (Graham and Wiener 1995). Where possible, the comparisons should be quantitative, but qualitative studies would suffice where meaningful qualitative measures do not exist or are being developed.

The NRC's rules, in particular its Standards for Protection Against Radiation, seem complicated by sources of risk tradeoff and likely to benefit from an examination with RTA. The NRC is an institution of specialists charged with reducing specific risks. Moreover, due to jurisdictional boundaries, other agencies are responsible for risks outside of NRC's purview, including countervailing risks caused by NRC's rules. These issues demonstrate complexities due to bounding roles, and is exemplified by EPA's responsibility to protect human health and the environment from hazards beyond radiation (EPA 2000, EPA/NRC 2002) and OSHA's responsibility to assure safe and healthful working conditions in the presence of all hazards (NRC/OSHA 2013, DOL 2018b). Evidence of omitted voice is provided by NRC's reliance on BEIR VII for risk estimates. That report is informed primarily by research from the Radiation Effects Research Foundation on atomic bomb survivorship, and some critics claim that the voices representing other research are dismissed too easily (Fabrikant 1981, Goldman 1996, GAO 2000, Calabrese 2007, Luckey 2008, Aleta 2009, Tubiana et al. 2009, Vaiserman 2010, Suzuki and Yamashita 2012, Calabrese 2013, Doss 2013). Old-technology bias is exemplified by a reluctance to deviate from the LNT model and other conservative measures reflecting the status quo (GAO 2000, Calabrese 2013). Heuristic processes align with the assumption that all radiation is harmful and should be avoided (Walker 2000), and cancer, DNA lesions, and other mutagenesis are likely to rank higher than other risks, particularly in terms of public perception. Regulations enforce compensating behaviors via the NRC's policy of maintaining exposures as low as reasonably achievable (ALARA), which over time has resulted in acceptance of actions that pile conservatisms on top of other conservatisms (GAO 2000, Walker 2000, Jones 2005). Aside from these blatant examples of risk tradeoff sources, the NRC has formally demonstrated a desire to practice risk-based policymaking according to a 1995 final policy statement on the matter (NRC 1995). NRC's radiation-risk-mitigating limits predate its acceptance of this policy, however, and were developed with deterministic methods (NRC 2007). Finally, the NRC is under some pressure to reduce its dose limits in a manner conforming to recommendations from the International Commission on Radiological Protection, and many consider the existing rules to provide sufficient protection (Cool 2012).

A disparity reflected by the NRC's dose-based cleanup criteria, 0.25 mSv y^{-1}, is that workers accomplishing cleanup are subject to 200 times the radiation-induced solid-cancer risk of a theoretical critical group representing the general population based on estimates from BEIR VII and the rules regulating their exposures. Moreover, cleanup workers are exposed to a large number of non-radiological industrial health and safety hazards. Heavy equipment operation, the use of power tools and torches, demolition, earthmoving, transportation, lifting and rigging, and the handling of hazardous chemicals and cleaners are examples of health and safety challenges (i.e., tradeoffs) that are encountered while cleaning up small amounts of radioactive contamination.

The environmental burden caused by cleanup is also considerable. Since as early as 1978, EPA has recognized that ecological impacts are caused by land restoration and cleanup (EPA 1978). Natural ecosystems, managed ecosystems, and wildlife may be negatively affected by cleanup efforts (EPA 1978, Burger et al. 2007). In some cases, the effects may be irreversible, as in the destruction of habitats and slow-growing lifeforms such as lichens (EPA 1978). Ecological environments are slow to recover, and resolving the effects of cleanup is not as easy as backfilling or revegetating. Cleanup work is accomplished with equipment that burns fossil fuel, and it is not unusual for a large cleanup project to burn tens of thousands of gallons of diesel fuel. Similarly, innocuous levels of radioactive waste are transported across the country by diesel-burning conveyances. Moreover, a large commitment of land is required to bury and manage these wastes. Where soil remediation occurs, backfill and topsoil must be stripped from another location to restore the remediated site, and such resources are not easily renewed. In addition to leaving the donor site barren, the removal and transportation processes also require the use of diesel-burning heavy equipment and trucks.

As these examples demonstrate, a number of countervailing risks are introduced by the NRC's cleanup criterion that, according to BEIR VII estimates, corresponds to approximately two solid cancers developing (not deaths) per 100,000 people. If the LNT model is incorrect, if a threshold exists, or if hormesis is a legitimate factor, the countervailing risks are experienced without any corresponding reduction in population risk. Moreover, cleanup criteria do not correlate to exposures shared by a large population; rather, they correspond to the peak dose to a theoretical, average member of a small "critical group" who, at some point over the next 1,000 years, builds and lives in a house on the contaminated land (NRC 2006). During that time, this hypothetical individual is expected to drink from a contaminated well, breathe contaminated air, and grow vegetables and raise animals on contaminated farmland that serve as his (a reference man is modeled) primary source of food (NRC 2006). This conservative, bounding theoretical scenario is called "resident farmer" (NRC 2006). Thus, the dose this limit represents is an intangible dose; in fact, a radiation detector has not been invented that measures resident-farmer dose. Rather, the dose limit is translated with computer models into surface or mass concentrations against which comparisons can be made with field and laboratory equipment (NRC 2006). There is considerable uncertainty associated with such models (NRC 2006), and according to the behavioral norms discussed elsewhere, it is common to pile conservatism on top of conservatism in an attempt to reconcile uncertainty and keep exposures ALARA. Finally, international recommendations include cleanup criterion as low as 0.01 mSv (IAEA 2006b), which would further exacerbate possible tradeoffs. EPA, some Agreement States, and France, German, Spain, and the United Kingdom already have lower cleanup limits than the NRC (EPA 1997, Meck 2012, Commonwealth of Massachusetts 2016, State of New Jersey n.d.).

Data pertaining to countervailing occupational health outcomes are available from a variety of sources. Nationally, the U.S. Department of Labor's Bureau of Labor Statistics collects and publishes data on mortality according to its Census of Fatal Occupational Injuries (CFOI) and on morbidity according to its Survey of Occupational Injuries and Illness (SOII). Data pertaining to occupational outcomes are also available from national surveillances not specific to occupational health. Such secondary sources include the National Health Interview Survey (NHIS) and the National Health and Nutrition Examination Survey (NHANES). At least 15 states have received funding from the National Institute for Occupational Safety and Health (NIOSH) to accomplish surveillances activities within their borders (Souza et al. 2010). State surveillances provide important information on local occupational health differences and intervention activities (Souza et al. 2010). Moreover, state surveys sometimes provide superior data in terms of occupational illness and particularly in the case of chronic illness (Souza et al. 2010). It is not possible to discriminate radiation workers from other workers; however, and important differences may exist between these groups. For example, worker health and safety risk estimates are possible for construction workers, but radiological construction workers may participate in more robust health and safety programs than the average construction worker.

Risks pertaining to airborne pollutants, such as the emissions released from the burning of fossil fuels, have been quantified by other researchers and associate ambient airborne pollution exposures to mortality from all-causes, cardiovascular disease, and respiratory disease (Pope et al. 1995, Pope et al. 2002, Pope et al. 2004, Hoek et al. 2013). Specifically, Kloog et al. examines the short-term and long-term effects of PM2.5 exposures on population mortality (Kloog et al. 2013), and Pope and Dockery have published a meta-analyses connecting fine particulate air pollution and adverse health effects (Pope and Dockery 2006).

Characterizing ecological risks with quantitative measures for comparison purposes is more difficult. Traditionally, the bioindicators researchers rely on relate to either ecological health or human health (Burger and Gochfeld 2001). Arguably, human health assessment is the easier of the two. Ecosystems cannot speak for themselves and are unable to respond to surveillances in the same manner as humans. Moreover, humans are a single species and experience a relatively limited range of health endpoints, whereas ecological health assessment must consider many species, endpoints, and higher order interactions (Burger and Gochfeld 2001). Since as early as 1978, EPA has recognized that ecological impacts are caused by land restoration and cleanup (EPA 1978). Natural ecosystems, managed ecosystems, and wildlife may be negatively affected by cleanup efforts (EPA 1978, Burger et al. 2007). In some cases, the effects may be irreversible, as in the destruction of habitats and slow-growing lifeforms such as lichens (EPA 1978). Ecological environments are slow to recover, and resolving the effects of cleanup is not as easy as backfilling or revegetating.

The NRC's low-level waste management policymaking may also be conflicted in a manner that causes risk tradeoffs. The NRC does not regulate waste disposal according to dose. Instead, waste is defined in the NRC's regulations with complex language and wastes meeting the definition are regulated. The disparities represented by this approach are due to the fact that wastes conveying the same level of induced-cancer risk may be disposed differently or not at all. In turn, populations benefiting from regulated disposal will have their exposures controlled whereas populations interfacing with unregulated disposals or releases will not. Since radiation-induced cancers are related to effective dose, not the words bureaucrats use to populate glossaries, risk tradeoffs may be occurring.

Evidence Supporting a Paradigm Shift

The research contributing to this paper identified certain concise evidence that supports the need for a radiation policymaking paradigm that considers risk tradeoffs.

1) In 1978, EPA's Office of Radiation Programs published a Technical Report entitled *The Ecological Impact of Land Restoration and Cleanup* recognizing the short and long term consequences (i.e., tradeoffs) associated with the Agency's policies. The report was written "primarily from the viewpoint of radiation protection" according to the Deputy Assistant Administrator for EPA's Radiation Programs at the time (EPA 1978). It is valuable to note that this report was published fewer than eight years after the EPA was created and just three years after the NRC began its operations. From this evidence, we can conclude that radiation policymaking has been known to be associated

with risk tradeoffs since before either agency was considered a mature organization.

2) Since at least 1985, just 10 years after opening its doors, NRC has understood that prescriptive policymaking interferes with the commission's ability to make risk-superior decisions (NRC 1985). This evidence comes from NRC's Office of Nuclear Reactor Regulation and is published in its policy on future reactor designs, NUREG-1070. The document contains a call for development of "forward-looking policy" that explores "safety-cost tradeoffs within the framework of permissible risk-risk tradeoffs" (NRC 1985).
3) In 2002, a DOE top-to-bottom review team concluded that since establishing its Office of Environmental Management in 1989, the Agency had spent more than $60 billion on cleanup without realizing a reduction in actual health risk because of the number of ecological, temporal, and human health tradeoffs involved (Burger et al. 2004). A follow-on study examining 36 sites in 17 states with an environmental management mission concluded that DOE needed a decision making tool capable of balancing a number of different ecological and health risks (Burger et al. 2004).
4) According to a 2016 article concerning the disaster Fukushima Daiichi and related mortality, nearly 2,000 deaths can be attributed to policymaking accomplished according to the paradigm that any amount of radiation is harmful and should be avoided. The article was published in the *Annals of the International Commission on Radiological Protection* and concludes that the number of people killed as a consequence of evacuating the prefecture to

> avoid low-dose radiation exceeded the number of Fukushima inhabitants who were killed directly by the earthquake and tsunami (Hayakawa 2016).

A key takeaway from these findings is that the top federal agencies concerned with radiation protection have understood, almost since their inception, that risk tradeoff is a pervasive feature of their policymaking. Nonetheless, these agencies continue to base their rules and regulations on a policymaking paradigm that reduces dose but not necessarily risk. As demonstrated by observations from Fukushima Daiichi, adverse health outcomes are possible when the countervailing risks associated with dose-limiting policymaking are ignored.

Education Needs

Finally, this paper would be negligent if it failed to emphasize a need for education. A new policymaking paradigm will not be realized unless (1) the public is educated on the genuine risk presented by exposure to low levels of environmental radiation and (2) radiation protection professionals and practitioners are better trained to communicate such risk to the public.

It is a fact that the risks associated with low doses of radiation are very small or nonexistent; a claim that is substantiated by the risk estimates and narrative provided by BEIR VII (2006). In the end, we find that environmental radiation is not a very effective carcinogen. While adverse non-cancer health effects are also possible, what the public typically recognizes as “radiation sickness”, such outcomes require very large exposures – far above the levels with which dose-limiting policymaking is concerned. Finally, radiation exposure is not associated with the perverse somatic and genetic effects sensationalized by Hollywood. While dose-limiting policymaking is concerned with preventing damage leading to DNA mutations, these mutations are “broadly similar to the types that occur naturally” such as changes leading to oncogenesis (NAS 2006). Radiation exposure does not endow anyone with any special powers or abilities or cause tails or other extra appendages to spontaneously sprout.

Public sentiment does not align with the statements of fact comprising the previous paragraph (Jordan 2016). In part, this is because the media and other social experiences are working harder and faster than the science programs in our primary and secondary schools. Thus, educational programs necessarily involve an element of un-teaching previously conceived attitudes and beliefs where radiation is concerned. But some blame is due to the radiation protection professionals who are responsible for educating and communicating risk to the public. In a 2018 article published in *Radiation Protection Dosimetry*, a case is made for essential characteristics of risk communication. These characteristics include use of techniques such as understanding how to frame information given a person’s values, building trust, and fully considering how information is provided (Murakami et al. 2018). We cannot expect practitioners to understand the dual nature of risk communication - as professionals and humans – unless they are trained and educated accordingly.

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