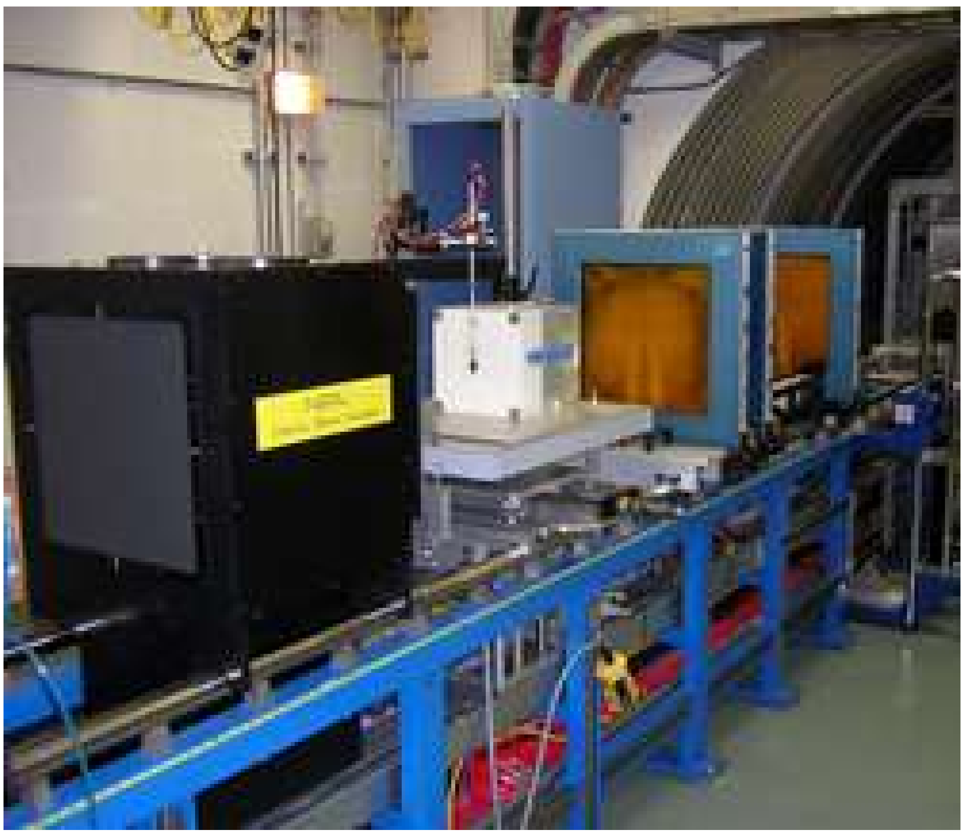
REPORT OF THE HEALTH PHYSICS SOCIETY RESEARCH NEEDS TASK FORCE JULY 2021



HPS

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1. Executive Summary

Radiation protection related research is critical to our nation in the following respects:

- Protecting human health and the environment
- Extending our understanding of the science
- Maintaining our scientific infrastructure, including a trained and experienced workforce and state-of-the-art research facilities
- Supporting effective risk management and efficient resource allocation in reducing overall health risk to occupationally exposed workers and the public in both day-to-day operations and emergencies

The Task force has broken down research needs into nine broad areas, as follows:

- Nuclear Fuel Cycle and Nuclear Power Production
- Radiation Protection through Improved Estimates of Radiation Effects/Risk at Low Doses
- Use of Radiation for Medical Care
- Improved Measurement of Radiation through Instrument Developments
- Decontamination and Decommissioning of Nuclear Facilities
- Exploration of Space
- National Defense
- Emergency Response to Nuclear Events
- Prediction of Fate and Effects of Radionuclides in the Environment

Each area has a number of associated **research goals** with supporting sub-goals. This enumeration is intended to provide the research direction needed to fill gaps in our knowledge, and to provide the seeds of ideas for relevant research.

The idea of **research synergy** is presented to encourage collaborative discussions, thought, and activities that cut across specialties, with the expectation that the collaborative effort will multiply the research effort, producing better and more abundant results with smaller input of resources, across multiple disciplines. If we ensure that researchers are communicating, we can limit redundancy and increase productivity. We can create the conditions where one line of research is furthering several others, ensuring knowledge gaps and needs are fulfilled faster and with fewer resources. Communication and data sharing between research groups is a critical enabler and should be highly encouraged. In addition, funding agencies should recognize that their funding decisions have a broader impact on the research landscape than in just the program being considered for funding.

The Task Force strongly recommends **research prioritization** based on the following considerations intended to maximize the impact of limited research dollars: the magnitude of risk reduction, potential resource savings (on application of the fruits of the research), degree of operational impact, clinical impact, decision making impact and synergy with other areas of research.

The amount of experience and expertise across the radiation safety community brought to bear on this issue is considerable, and reflects the importance the Health Physics Society places on the research enterprise. This and following efforts are critical to broadening and deepening our understanding of the nature of radiation and radioactive materials, maintaining an educated workforce, good stewardship of limited resources, and prudently managing associated risk.

2. CHARTER

Health Physics Society Research Needs —Team Charter

PROBLEM DEFINITION	As an adjunct to NCRP's "Where are the Radiation Professionals (WARP)?" initiative, Health Physics News (September 2016) focused discussion on the issue with headline article "Are Health Physics Academic Programs in Trouble?" A major factor identified in declining enrollments and the closing of academic programs was the lack of funded research.[1] The HPS, along with ORAU and Oak Ridge National Laboratory, hosted a Radiation Protection Research Needs (RPRN) Workshop on June 5-6, 2017. The outcome of the workshop was a strategic research agenda focused on near-term radiation protection research needs of Federal agencies over 3-to-5-year time horizon.
PURPOSE	• Task Force will identify options for how the HPS can best support the research needs of the federal agencies and industry, while supporting the research funding for academic programs. The recent Workshop Summary report (Strategic Research Agenda) and desire to maintain momentum will serve as the catalysts for this effort.
IMPORTANCE	• Identifying research needs and communicating these needs to agency and congressional stakeholders is of critical importance to the protection of radiation workers and the public, to the HPS and the HP profession. Research funding is a necessary condition for ongoing viability of HP academic programs, preservation of radiation protection expertise, and the maintenance of a pipeline of adequately-trained radiation protection professionals at all levels.
RESTRICTIONS (INCLUDING BUDGET)	• Maintain appropriate collaboration between radiation protection research needs at academic programs and national research efforts at national labs
SCOPE	The HPS Research Needs task force will make recommendations to the HPS Executive Committee on path forward for supporting and advancing research needs in radiation protection. Specific areas to address include: • Identify scientific drivers supporting the national needs in radiation protection research • Review the Strategic Research Agenda developed as an output of the RPRN Workshop, and determine how this can be a living document that reflects the radiation protection research areas critical to the completion of the nation's missions. • Assess ongoing status of radiation protection research funding and needs in the U.S., including federal, state and private sector funded research • Support communication of research needs to appropriate stakeholders, including Congressional appropriators on Capitol Hill

[1] Research in sustaining the human capital pipeline, including but not limited to the recruitment and retention of health physics expertise from universities and other health physics stakeholders, such as DOE national laboratories, federal agencies, and private industry.

EXPECTED OUTCOMES	• Recommendations to the HPS Executive Committee regarding how HPS can best support radiation protection research needs for both academic programs, as well as national research efforts, such as those at national laboratories.
COMMENCEMENT	• As soon as the Charter for this Task Force is approved by HPS Executive Committee; no later than September 30, 2017. This needs to be modified
DELIVERABLES, MILESTONES & CONCLUSION	Deliverables include the following: • Recommendations on how the HPS should proceed and expand on the activities conducted at the Workshop—for example, should the HPS reestablish the Research Needs Committee? • Assessment of whether this activity can be addressed by other standing HPS committees, such as the Academic Education Committee (vs. maintaining close coordination with the AEC) • Recommendation report on how HPS should manage identification and communication of radiation protection research needs Milestones include the following: • Milestones will be identified in project management plan for activities over next several months, concluding in May 31, 2018

3. Background

In order to protect humans and the environment when using ionizing radiation for the advancement and benefit of society, accurately quantifying radiation and its potential effects remains the driver for ensuring the safety and secure use of nuclear and radiological applications of technology. In the realm of radiation protection and its various applications with the nuclear fuel cycle, (nuclear) medicine, emergency response, national defense, and space exploration, the scientific and research needs to support state and federal radiation protection needs in the United States in each of these areas are still deficient.

With this realization amidst atrophying national expertise in radiation protection, the Radiation Protection Research Needs (RPRN) Workshop was held in Oak Ridge, Tennessee, on June 5–6, 2017. The workshop was motivated by outreach and strategic alignment activities of the Oak Ridge National Laboratory (ORNL) Center for Radiation Protection Knowledge (CRPK) with its counterparts at Oak Ridge Associated Universities (ORAU), both organizations with a historical legacy both nationally and internationally health physics research, as well as operational programmatic, education, and training support. This workshop, hosted by ORAU, ORNL, and the Health Physics Society (HPS), facilitated critical dialogue amongst radiation protection stakeholders in the federal and state governments and the scientific communities, including the Department of Energy (DOE) national laboratories, academic institutions, and non-governmental organizations (Dewji et al. 2017).

Prior to the RPRN Workshop, the National Council on Radiation Protection and Measurements (NCRP) had identified an impending critical crisis in human capital and announced an initiative to address this critical need in NCRP Statement No. 12, "Where Are the Radiation Professionals (WARP)?" (NCRP 2015). NCRP identified investments that must be made to maintain staffing levels, as radiation protection personnel retire, through the development of a strategic recruitment and retention pipeline for radiation professionals. The human capital crisis persists, and recruitment of radiation protection personnel from health physics programs and from complementary fields (e.g., engineering, physical sciences, industrial hygiene, mathematics, social sciences) must aggressively ensue.

In an alternative strategy, the ORNL CRPK and ORAU identified research-based drivers to the nation's radiation protection research needs in government and industry. Their approach, which spans nuclear energy, medicine, and security, is based on their roles as stakeholders; as research and development (R&D) organizations; and as providers of operational mission support, education, and training. Radiation protection research needs are evolving based on current technological requirements and their associated governing policies. Under current conditions (i.e., financial, economic, energy, defense), R&D in the field of radiation protection calls for cooperation among governmental agencies, emergency responders, research organizations, and the academic community.

The objectives in radiation protection relevant to current challenges, needs and gaps in radiation protection science were identified in the RPRN Workshop (Table 1).

Table 1. Oak Ridge Radiation Projection Research Needs Workshop: Critical National Radiation Protection Research Objectives.

Objective 1: How can the **radiological protection** of workers, the public, and the environment from radiation exposures due to occupational and public exposures, (nuclear) medical procedures, nuclear safety and security events, and space exploration be improved?
Objective 2: How can **monitoring**, **detection**, and **assessment** of radioactivity in the environment be improved?
Objective 3: What can be done to advance the understanding of **biological effects** of exposure to ionizing radiation (e.g., low-dose radiation effects) to allow optimization of the use of radiation, radiation protection, and how these effects/results will be integrated into regulatory policy?

A broad spectrum of issues require attention and must eventually be addressed to ensure that radiation protection programs in the energy, industrial, defense, and security sectors continue to meet these emerging needs, through both conducting focused research in critical scientific/mission areas and advancing training and developing of skilled radiation personnel. At the most fundamental level, the RPRN Workshop underscored the need for the identification of research drivers and existing/desired capabilities to capture the projected radiation protection needs vis-à-vis current capabilities (i.e., state of practice) in the purview of challenges and required innovation (i.e., desired state of the art) to bridge the gaps, and identify resources required – i.e., human capital, technical infrastructure, etc. – to fulfill these needs.

4. INTRODUCTION

Scientific research has provided fundamental insight into the world around us, our history, human interactions and contributed to our growing body of knowledge over every aspect of our existence. Scientific research has made us healthier, safer and better stewards of our world. Scientific research forms the basis of all the technology that we rely on in our day to day lives, and will continue to grow and enhance the lives of those that follow us. As with most human endeavors, there are costs associated with such activities, and as our knowledge grows, it becomes more and more challenging to tease further knowledge out of Mother Nature, often becoming commensurately more expensive. In an environment of growing costs and constrained resources, it becomes difficult for any single support stream to provide all of the resources every deserving project needs. We must therefore recognize these resource constraints, but also acknowledge that such a great endeavor deserves deliberate and focused effort on those projects that will advance human knowledge and capabilities, delivering the most return on investment.

Radiation safety research is important because it informs health risk management, occupational safety, minimization of ancillary risk associated with the use of radiation in medicine, and improved environmental stewardship. Medical radiation protection is critical due to the increasing use of procedures that expose patients to radiation, and the high concern engendered by these increasing exposures that include cancer (radiotherapy), heart disease (nuclear medicine), and CT scans (dx radiology). Environmentally derived radiation exposure is also of interest, for example monitoring the food supply after Fukushima, environmental monitoring associated with nuclear treaty verification, and environmental impact of the radiation/radioactive materials on flora and fauna. There are radiation related research questions related to national security and homeland defense, to include the nuclear weapons production and maintenance cycle, nuclear weapons and radiation dispersal device modeling and radiation detection for interdiction. Regarding nuclear energy, research is needed to safely operate, decommission, and clean up the aging US fleet of reactors. Finally, note that many of these areas overlap, are interrelated, and/or necessitate collaboration with specialists in other fields.

The health physics community in the United States of America has seen research support and direction erode over time due to budget constraints, lack of public support for nuclear power, and other competing priorities. Our defense focus has been the wars in Iraq and Afghanistan, not the potential mutual nuclear destruction that was the primary concern during the Cold War with the Soviet Union. Accidents like Three Mile Island, Chernobyl and Fukushima have led the public and our government representatives to look to non-nuclear sources of power. Environmental issues, such as Yucca Mountain and the WIPP, have been expensive and contentious, causing lawmakers to turn away from these challenges that have little public support and where strong negative emotions hold sway. Radiation related medical research is the one area that has seemed to thrive throughout all of these changes.

Health physics supports the nuclear fuel cycle, medical use of radiation and radioactive materials, the nuclear weapons enterprise and environmental stewardship. We recognize that our infrastructure and our top experts in the field are aging. Radiation and nuclear professionals, as well as policy makers, across the United States need to acknowledge that it is imperative that we maintain our nuclear and radiological expertise in the form of human capital, facilities and the technological tools required to perform our various functions. If we allow these things to wither due to inattention, lack of planning and lack of resources, there are serious national security implications. Sponsorship of cutting-edge research is at the heart of maintaining all of these interconnected elements, and ensuring that the United States retains technological leadership and dominance in this important area of endeavor.

We should recognize the secondary benefits of maintaining strong research support and direction. We need to maintain the domestic pool of people who understand the science and engineering associated with the nuclear fuel cycle, nuclear weapons and nuclear power, as well as supporting knowledge and skill sets in radiation safety and environmental management issues. We need to maintain the scientific infrastructure at our laboratories and universities, so that we may continue to grow knowledge and nurture and sustain the human capital. We must acknowledge that defense and energy are important to the fate and standing of the nation as a whole.

Though there are many challenges, the availability of new research tools will enable us to solve longstanding, important societal problems leveraging scientific knowledge resulting from modern research initiatives, that may have been previously intractable or prohibitively expensive. It is prudent to identify areas of research that provide the most return for the resource investment, which would then inform the decisions determining particular research directions and specific projects.

Within the area of radiation sciences, with this end in mind, cooperative research consortia that pool and direct resources to the best value projects have been established, particularly in Europe. Strategic research agenda have been established in several related areas the funnel resources to the projects assessed to give the most return on investment, based on the considered opinion of subject matter experts and policy makers. The European Radiation Dosimetry Group (EURADOS) has developed such a document focusing on radiation dosimetry[1], and feeds into the Open Projects for European Radiation Research Area (OPERRA) project designed to coordinate and administer future calls for research proposals in radiation protection on the behalf of the European Commission. The Multidisciplinary European Low Dose Initiative (MELODI) has produced a similar document focused on "the establishment and updating of a long term (>20 years) Strategic Research Agenda (SRA) for research on low dose risk for radiation protection in Europe."[2] The European Radioecology Alliance (ALLIANCE) was assembled to ensure the "…long-term governance of research in radioecology…", and has also produced an SRA.[3] The European Platform on Preparedness for Nuclear and Radiological Emergency response and recovery (NERIS) has developed version four of their SRA[4] as well as a roadmap to aid in long term planning.[5] The European Alliance for Medical Radiation Protection research (EURAMED) has "…the goal of jointly improving medical care and its medical radiation protection issues through sustainable research efforts."[6], and has produced the first edition of a SRA in support of its goal.[7] The European Joint Programme for the integration of Radiation Protection Research (CONCERT) "…is operating as an umbrella structure for the research initiatives jointly launched by the radiation protection research platforms MELODI, ALLIANCE, NERIS and EURADOS. CONCERT is a co-fund action that aims at attracting and pooling national research efforts with European ones in order to make better use of public R&D resources and to tackle common European challenges in radiation protection more effectively by joint research efforts in key areas."[8]

The US health physics community has come to recognize the criticality of developing and maintaining a strategic research agenda in support of health physics research priorities in order to maintain current knowledge, develop additional scientific insight, develop human capital and to maintain our scientific leadership and infrastructure in this important area. This document is an effort to address these crucial needs.

1. Visions for Radiation Dosimetry over the Next Two Decades - Strategic Research Agenda of the European Radiation Dosimetry Group, EURADOS Report 2014-01, May 2014.
2. Strategic Research Agenda of the Multidisciplinary European Low Dose Initiative (MELODI) – 2017.
3. Short- to medium-term research priorities in radioecology to improve the scientific basis and reduce uncertainties in human and environmental risk assessments, increasing radiation protection of humans and wildlife, ALLIANCE Statement – June 2017.
4. Strategic Research Agenda of the NERIS Platform, Version 04, November 2017.
5. NERIS Roadmap, Version November 20, 2017.
6. http://www.eibir.org/scientific-activities/joint-initiatives/european-alliance-for-medical-radiation-protection-research-euramed/, accessed 28 Feb 2018.
7. Common strategic research agenda for radiation protection in medicine, Insights Imaging (2017) 8:183-197.
8. http://www.concert-h2020.eu/en/Concert_info/About_CONCERT, accessed 28 Feb 2018.

5. RESEARCH GOALS

The research goals delineate broad areas of interest that are germane to the health physics community. Under each broad goal are a number of areas of interest that have been identified and described by the community as needing improved understanding. It is intended that specific lines of research be established in support of each of these areas, with reference to the prioritization and justification considerations and potential synergies between the individual lines of research. It is understood that funding and research institutions will have their own priorities to consider in addition to those outlined, in the overall determination of individual research agendas.

5.1. Support Nuclear Fuel Cycle and Nuclear Power Production

Objective

Radiation protection is an essential element in all phases of the nuclear fuel cycle and nuclear power production to ensure safety. Nuclear power has proven to be a reliable, environmentally sustainable, and cost-effective source of large-scale electricity. In the interest of continued technological improvement, further improvements in operational reliability, economics, and safety under normal and transient conditions are being pursued worldwide. Congress has invigorated its interest in the future of nuclear energy needs in the U.S. and has directed the Department of Energy (DOE) to develop enhanced fuels, such as Accident Tolerant Fuel (ATF)[2] for light water reactors to improve safety in the event of an accident. In addition, the U.S. Nuclear Regulatory Commission (NRC), has been also asked by Congress to look into two new types of reactors: Small Modular Reactors (SMRs) which are smaller versions of the traditional Light Water Reactor (LWR) designs and Advanced Reactors (non-LWR designs). NRC must be ready to review potential applications for non-LWR technologies effectively and efficiently – which includes potentially new and differing radiation profiles of this next generation reactor. The HPS supports research that enables the development of innovative and safe nuclear power production by supporting research for new technologies that could provide even more effective radiation protection to workers, the public and the environment.

This can be accomplished by: 1) research and development of ATF and related dosimetry to understand the behavior of ATF and SMRs during operation and during design basis and beyond design basis events; 2) revising or developing new and/or improved dose modeling for SMRs in order to assess operation and emergency response functions; 3) development of acceptable waste handling and disposal options for ATF and SMRs; and 4) incorporation of new shielding technologies during initial reactor design is needed to minimize potential future occupational exposures during operation for SMRs.

Stakeholders- Regulators (DOE, NRC, EPA), FEMA, elected officials, ANS, HPS members, nuclear utilities and vendors, the public

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[2] ATF is a term used to describe new technologies that further enhance the safety and performance of nuclear materials. This can be in the form of new cladding and/or fuel pellet designs.

<u>Research Goal 1</u> - *Research and development (R&D) of LWR fuels with enhanced accident tolerance is needed to achieve higher fuel and plant performance, which in turn would provide enhanced safety during potential design basis and beyond design basis accident conditions.*

- The operating licenses of approximately half of the US's current reactor fleet will have expired by the mid-2030s, and operators seeking license renewals should be able to take advantage of the benefits of ATF if they are available by the mid-2020s.
- ATFs are a potential game changer for the U.S. utilities as it has the potential to endure the loss of cooling in a reactor core for longer than current fuel designs and widen the existing safety margin for existing nuclear plants.
- ATF also can improve the performance of existing nuclear plants with longer-lasting fuel and pave the way for licensing fuels for advanced reactors (non-LWRS) and SMRs.
- Research in fabrication, transportation, storage, and in-reactor performance will allow the US to be a leader in development of ATF for improved safety performance in reactors.
- Research in determining the differences in fuel system phenomena, including cladding oxidation, pellet-cladding interaction, pellet relocation and dispersal, and cladding embrittlement and fragmentation are needed to ensure that requirements for transient and accident analyses of a nuclear power plant are met.
- Understanding of the specifics of the behavior of ATF is essential to ensure that in designing and constructing a nuclear power plant, calculations must be performed to verify that, in the planned and anticipated regular work tasks, the collective annual dose of the plant unit personnel does not exceed the occupational dose limit prescribed by the NRC, averaged over the designed operational life of the plant.
- Assessing the dosimetric impacts (especially internal dosimetry) of different materials chemistry is essential when compared to existing reactor designs.
- Incorporation of used fuels (contain higher concentrations of mixed fission products) poses different challenges with regard to dose when compared to fresh UO_2.

<u>Research Goal 2</u> - *Research to better characterize the radioactive constituents of ATF and SMRs to document and assess the radionuclide components of new fuels to assess the viability of scalable emergency planning zones (EPZs).* Revised and/or improved dose modeling with new ATF will be needed for operation and emergency response.

- Recognizing that the NRC's regulations primarily have focused on large LWRs and that the safety and performance attributes of SMRs might differ from those of large LWRs, the NRC and industry have worked for more than two decades to assess the viability of scalable EPZs—EPZs with radii of less than 10 and 50 miles—for SMRs and other advanced reactor designs
- Research for advanced reactor design includes the development of codes suitable for confirmatory analysis of high-temperature gas-cooled reactors (HTGR), sodium fast reactors (SFRs), and molten salt reactors (MSRs).
- Research for assessing the new fission product inventory of ATF and resulting revised dispersion models for development of appropriate EPZs and consequence analyses during emergencies
- Research on the types of systems and components designed for SMRs should be conducted to ensure that any work stages that must be performed at a high dose rate (during outage or for decommissioning) is small and their duration is short.
- New nuclear safety codes that are developed represents a challenge to regulators due to:

- Unfamiliarity with the codes, the "learning curve" that must be overcome and consideration of any user impacts (i.e., developing best practice guidance)
- Understanding the physical phenomena and modeling requirements that are required for these advanced reactor designs
- Computer equipment needs may exceed the USG existing high performance computing system capability and may require access to significant computer hardware (i.e., additional high-performance clusters)
- Need for validation and assessment of the analytical codes

Research Goal 3 – ***Research for the development of acceptable waste handling and disposal options for ATF and SMR.***

- Nuclear power requires an accepted disposition pathway for nuclear waste.
- Used fuel behavior is becoming increasingly important in the United States given that the used fuel may need to maintain its integrity over an extended interim storage period and through transportation to an eventual repository for ultimate disposal. Research is needed to assess the impact for local or long-term storage.
- Development of acceptable waste handling and disposal options for ATF will help in obtaining public approval for SMRs if a disposal option is fully thought out and available at the time of commissioning.
- Components and parts should be designed and selected in such a way that radioactive materials do not unintentionally accumulate in them.
- Research conducted to reduce the accumulation of radioactive materials in individual components and systems should be assessed and anticipated in such a way that the accumulation points can be shielded and, if necessary, decontaminated easily at the end of plant life.
- Radioactive waste releases can be reduced by the treatment of radioactive materials. Research for innovative methods for potential liquid treatment methods include, for instance, mechanical filtration, ion exchange, centrifugation, evaporation and chemical concentration.

Research Goal 4 – ***Research and incorporation of new shielding technologies during initial reactor design is needed to minimize potential future occupational exposures during operation of SMRs***.

- The locations and radioactivity makeup of the fuel during normal operation of a SMR must be assessed in the design phase. Radiation sources include, for instance, the reactor and the systems related to the reactor, and radioactive waste, waste handling systems and spent fuel.
- Radiation shields need to be designed with adequate safety margins for SMRs and ATF usage. In addition, assessment of the transfer and storage of spent fuel and components removed from the reactor, and on the areas where people work continuously to handle such waste needs to be assessed.
- Large uncertainties in dose estimates from existing radiation shielding models used for ATF design and SMRs during operation could result in inaccurate assessment of occupational dose (an overestimate) and/or inappropriate emergency response (too small or too large of an area for an EPZ).

- The environmental pathway data for fuels in a different chemical form is expected to be vastly different from what is modelled in the current U.S. LWR reactor fleet.

5.2. Support Radiation Protection through Improved Estimates of Radiation Effects/Risk at Low Doses

Objective
Epidemiologic data from the atomic bomb survivors, workers, patients, and the public play a significant role in assessing cancer risks caused by radiation. These data provide information on risks from external and internal radiation exposures (acute and protracted) to high, moderate and low doses. These data are used by the radiation protection scientific and standard setting communities for establishing the radiation protection regulations for workers and the public.

Scientific and standard setting communities recognize the limitations of the above epidemiological data for determining radiation risks at low doses (less than 100mSv). Simply, without precise knowledge about the biologic processes by which low dose and dose rate radiation cause diseases, epidemiologic data alone cannot provide inclusive scientific evidence. Currently, the risks from exposures to low doses are generally estimated by extrapolation using the linear-non-threshold radiation response relationship. Therefore, there is a need to pursue low dose and dose rate research at cellular, molecular and tissue levels to support the current radiation protection regulations, and to develop models that take account of these experimental studies that link the molecular mechanism to epidemiologic findings.

To understand risks at very low doses requires not only data from epidemiologic studies, but also an understanding of biological mechanisms to predict risks at dose levels below which possible effects can be directly measured. Further, due to declining resources and competence in radiation related research, the scientific communities and regulators need to discuss and identify a list of priorities for radiation protection research to ensure that the regulatory programs continue to adequately protect the workers and the public. Below is a list of suggested radiation protection research needed to increase our knowledge about low dose radiation risks, and to support the current regulations for occupational and public (children vs. adult) doses, medical exposures, emergency response and post-accident recovery, and radioactive waste disposal.

Stakeholders- This research area is relevant to all.

<u>Research Goal 1</u> – *Integrate epidemiologic studies with the basic sciences.*
- Support comprehensive, integrated, multidisciplinary research program that takes into account the latest advances in scientific knowledge and techniques to address the important issues related to radiation risks at low doses, and to increase our understanding of the health effects and risks associates with low dose and dose rate radiation exposures.

<u>Research Goal 2</u> – *Investigate and refine genetic risk estimates.*
- Support a genetic program that combines the epidemiologic studies with genetic studies (using animal model) to quantify potential risks and determine whether such risks exist. A major concern of the public as well as radiation workers related to low dose risks is whether

there are genetic effects that can be passed to their offspring that will result in an increased risk of cancer or other diseases.

<u>**Research Goal 3**</u> **– *Leverage molecular epidemiology to identify biomarkers of low dose radiation effects.***

- Design well-controlled molecular epidemiology studies to identify biomarkers of low-dose radiation-induced cancer and non-cancer health effects that are connected to diseases under investigations.

<u>**Research Goal 4**</u> **– *Support research on radiation mechanisms of action.***

- Use multiscale system biology approaches that would be expected to better describe the complexity of low-dose radiation-induced responses.
  - Assess whether there are scientific reasons for replacing the non-threshold paradigm with the threshold paradigm.

<u>**Related Goals-**</u>

- Educate and train future generations of radiation protection experts and researchers.
- Improve our ability to communicate radiological risks to the public.

5.3. Research Needs for Medical Applications of Radiation and Radioactive Materials

Objective

Research is essential to develop scientific solutions to address emerging national and global challenges in human health. For example, ionizing radiation is essential in the diagnosis and treatment of many potentially lethal diseases, such as cancer, heart disease, and arteriovenous malformations of the brain. Today, the use of radiation in medicine is safe, effective, and ubiquitous. Medical imaging procedures predominate the average radiation exposures of US citizens, e.g., from diagnostic computed tomography scans, radiation therapy for cancer, and nuclear medicine imaging for the diagnosis of heart disease. As the population continues to grow and age in the future, the prevalence of diseases and the corresponding utilization of radiation will increase. In addition, new applications of radiation, such as theranostics and heavy-ion beams are emerging in the US and abroad to diagnose and treat previously incurable diseases. For all these reasons, research on radiation protection in medicine will be vital to ensuring that radiation medicine is safe, high-quality, and widely available. The HPS supports research that enables the enhancement of radiation protection in the following areas.

Stakeholders-

- Medical staff involved in the use of radiation and radioactive materials
- Patients treated or diagnosed using radiation and/or radioactive materials
- Regulators, including the NRC, FDA, and state radiation control organizations
- Research faculty and staff at Universities and other medical research organizations
- Membership of professional organizations such as AAPM and ACR.

<u>**Research Goal 1**</u>**- *Improve methods for calculating radiation exposure to patients***

- Model all of the radiation exposure to all of the organs and tissues from all sources (e.g., therapy, diagnostic imaging, nuclear medicine).
- The models and algorithms developed should be fast, accurate (with known uncertainties), non-proprietary, and suitable for inclusion in FDA 510k-cleared systems for human use.

Research Goal 2- *Develop methods for personalized radiation dose and risk*

- The justification and optimization of radiation exposures from medical procedures should be based on a risk/benefit analysis that takes into account host- and treatment specific factors.
- Benefits, which are currently not explicitly included in prevailing methods to justify medical radiation protection practices, include a broad spectrum of effects, ranging from outright cures to palliation (alleviation of symptoms).

Research Goal 3- *Improve methods for calculating risk of radiogenic cancer and other late-occurring detriments*

- For some patients who receive radiation therapy, particularly children, improved dose and risk assessment capabilities are needed to develop better survivorship care plans (to monitor and manage late-occurring effects).
- Detriments include potentially fatal effects, such as second cancer, cardiac complications, and necrosis, and non-fatal effects including fertility complications, cataractogenesis, and fibrosis.

Research Goal 4- *Improve simulation methods to model advanced, emerging and next generation radiation therapy and imaging technologies*

- Proton and heavier ion beam therapies are emerging in the USA, Europe, and Asia.
- Research is needed to improve methods for radiation shielding design and verification, including stochastic and deterministic radiation transport codes, instrumentation, and metrology (e.g., calibration and traceability to the NIST).

Research Goal 5- *Improve understanding of the underlying physical mechanisms leading to radiation effects*

- Despite decades of research, the capabilities to predict radiation effects on biological systems from first principles remains very limited.
- Research is needed to model the physics of radiation biology, e.g., to be able to calculate the radiation damage caused to cells from radiations of various intensities and qualities.
- This should include multiscale simulation of radiation transport and dosimetry, anatomy and physiology, and response to injury.

5.4. Support Improved Measurement of Radiation through Instrument Development

Objective

The ability to accurately, conveniently, and economically measure radiation and radioactivity is the cornerstone of all of the various phases of Radiation Safety discussed in this document.

Without accurate measurements of radiation then the benefits from the use of radiation and the potential harm from the user of radiation cannot be properly assessed. Without convenient and affordable measurement tools, then sufficient type and quantity of measurement devices will not be available for routine or emergency use. Great strides from research on radiation detection fundamentals and instrumentation development were made by the US Government in the 1950's and 60's primarily to support weapons development. This research funding also then allowed the extrapolation of those instruments to support nuclear and radiation medicine, nuclear power, and industrial uses of radiation. Funding then dropped off until 2001, where Homeland Security started investing in the development of new technology.

Radiation measurement instrumentation for radiation safety and environmental safety purposes has always had a symbiotic relationship between government and industry. First came government research funding for the development new sensors and publication of the principles and validation of their operational limitations. This was then followed by commercial instrumentation companies to take those research products and industrialize them and produce standardized and supported products for the marketplace. It is essential for this funding of fundamental radiation measurement concepts and proof-of-concept measurement devices to continue. Funding of Governmental, University and Commercial developments in radiation measurement tools creates new sensors, allows for the acceptance of these new sensors, and trains the next group of users to understand these sensors.

Radiation accidents at Fukushima and Chernobyl have pointed out the need for large-scale and rapid measurements of radio-iodine in the atmosphere and in human thyroids. Rapid Sr-90 measurements of soil, seafood, and crops have also been identified as needs. Rapid bioassay measurements, especially for alpha emitters are also unmet needs important for both emergency response and routine operations.

Stakeholders

- US Government and Military personnel
- Medical professionals and support staff using radioactivity
- Reactor operators
- Personnel involved in Decontamination and Decommissioning
- Homeland Security and Emergency Response personnel
- University research faculty and staff

Research Goal 1- ***Improved neutron instrumentation***

- New physics accelerators, new medical accelerators, new operation regimes of reactors, and spent fuel storage at reactor sites all can generate neutron radiation fields. These need to be characterized for proper occupational and environmental safety.
- More affordable and portable devices to determine the neutron energy spectrum at occupational and public radiation levels
- Light-weight neutron instruments that have the appropriate spectral response to accurately determine the biologically significant dose and dose rate

<u>Research Goal 2</u>- *Indoor position logging*

- It is a very common task in radiation facilities to take a large number of radiation measurements at various locations within the facility. Considerable time is spent logging the exact position of these measurements. Outdoor measurement procedures can be improved by incorporation of GPS sensors in the instrument. That option needs to be made economically available for the large number of measurements that are made inside buildings or in areas otherwise inaccessible to GPS satellites.
- Low cost and easy to deploy anchors or sensors need to be developed that can be used to determine the instrument positions.
- Low cost, low power, and small sensors need to be developed that can be placed on or built into the radiation measurement instrument.
- An additional benefit would be the use of the sensing signal to transmit results from the instrument back to a central location.
- A standard should be developed to define the sensing protocol and the data transmission protocol for more universal deployment of various brands of sensors.

<u>Research Goal 3</u>- *Improve field-appropriate spectroscopy*

- Portable gamma spectroscopy instruments are very useful to determine the species of radioactivity and when properly calibrated can be just as accurate laboratory measurements. And, as compared to laboratory measurements, the results are known nearly immediately, and due to the large sample size, they can be more sensitive.
- The best devices today use HPGe sensors, but they are large, heavy, and expensive. The low-cost devices use NaI sensors, but they lack good energy resolution and therefore are limited to simplistic measurement situations. What is needed is a device approaching Ge in efficiency and energy resolution but without the burden of low temperature operation, and approaching the cost of NaI scintillators, but without the burden of photo-multiplier tube readouts.
- One current candidate is CZT semi-conductor sensors, however the current sensors are either too small or require complicated and expensive electronics. Research is needed in the crystal growth to make larger low-cost single crystals with good energy resolution.
- Another current candidate is SrI2 scintillator. Research is needed to further improve resolution and to create large-size readouts that do not involve large and fragile photomultiplier tubes, most likely close-packed arrays of SiPM or similar devices.

<u>Research Goal 4</u>- *Combination (radiological and chemical) detectors*

- This is an important item for Homeland Security. Now emergency responders must carry with them two different sets of instruments to assess radiological and chemical potential hazards. A single device for the most likely hazards would improve response.

<u>Research Goal 5</u>- *Direction-specific detectors*

- Current technology instruments are generally responsive to radiation in all directions. They rely on an experienced operator to move the sensor around to search for the source of the radiation. Or they require heavy shielding to be added in order to collimate the detector to be primarily sensitive to radiation from a certain direction, and then require the operator to aim the instrument in the desired direction. This requires a certain amount of skill in the operator and takes time to do.

- Simple low-cost instruments are needed for first-responders or other inexperienced users. These instruments would indicate both the dose rate and the primary direction from which it is coming.

Research Goal 6- ***Improvement to instrument ruggedness***

- The current generation of hand-held survey meters and field spectroscopy devices are not very rugged. For survey meters, the radiation sensor [GM tubes, ionization chambers, scintillation crystals] and the sensor readout [photomultiplier tubes] are generally the most fragile items. For gamma spectroscopy instruments, those with scintillation detectors and photomultiplier tubes have the same issues; those with HPGe detectors are even more fragile as they must deal with structural and electro-mechanical issues with keeping the detector cold.
- Research is needed to develop and qualify alternate sensors that can be smaller than GM tubes and ionization chambers and used in accurate dose-rate survey meters.
- Research is needed to develop and qualify alternate gamma spectroscopy sensors that have better resolution than NaI, do not use photomultiplier tubes, and do not require cooling.

Research Goal 7- ***Instrumentation that can detect alpha, beta, neutron, and gamma radiation***

- Many large industrial facilities have various types of radiation that must be measured periodically by the site radiation safety personnel. Homeland Security and other emergency response organizations need to be prepared to respond to situations where the type of radiation is not known in advance.
- Currently those organizations need to take multiple instruments with them, or make multiple trips.
- Research is needed to develop and qualify a single sensor, or a tightly integrated group of sensors that can indicate the presence of each of these radiation types separately.

Research Goal 8 - ***Development of instruments that are hardened against radiation damage***

- For use in high radiation fields, most current instruments have life-time limitations; after some integrated value of radiation exposure they are no longer effective. This causes limitations for use in certain applications, like high-range monitors in nuclear power plants, food or medical equipment sterilization area monitors, accelerator facilities, radiation medicine facilities, …
- Research is needed to develop sensors and associated electronics that can be used for longer times in medium-high dose rate fields.

Research Goal 9 - ***Definition and pathway for very low-level waste***

- Currently the US is spending a lot of money and using up valuable waste disposal space because there is not a clear definition and policy for the low-cost disposition of very low level radioactive waste. While the IAEA has created definitions and values of nuclide-specific radioactivity which could be released from control, the various US regulatory agencies have not endorsed this. While such releases are technically allowed, the various rules or practices in place make it very difficult to implement. Furthermore, for the situation of Radium and Thorium wastes, the various states have either no rules or have widely different rules.

- The promulgation of standard country-wide rules defining very low level waste that can be released from regulatory control, or sent to "normal" regulated sanitary landfills, is necessary to allow the development of common low-cost instrumentation to accurately and economically measure it.
- It is believed that no further government funded research into instrument development is needed, as long as the values established by the IAEA are followed, as current sensor technology us adequate.

5.5. Research Needs for Decontamination and Decommissioning of Nuclear Facilities

Objective

Radiation protection has a critical role in D&D of nuclear facilities ensuring the safety of workers, the public and the environment. While providing and even improving safety, substantial cost savings can be achieved through engagement of a number of research opportunities, as outlined here. Enabling research in radiation protection will improve D&D operations through providing new and improved technologies, credible dose assessment approaches for both radioactive and chemical waste constituents, measurement capabilities, and science- and risk-based risk decisions for waste disposition pathways. The HPS supports research that enables protective, compliant, and cost-effective D&D.

Stakeholders-

- State and Federal regulators
- Personnel engaged in decontamination and decommissioning operations
- The general public
- All personnel using radioactive materials or high-energy radiation producing devices (activation products)
- Personnel engaged in mining and industrial operations that produce TENORM
- Those engaged in nuclear power production and the nuclear fuel cycle (to include enrichment and nuclear weapons production)
- DOE national laboratory staff

<u>Research Goal 1</u> - ***Development and improvement of credible risk-based cleanup levels will***

- Improve ecological system transport models and parameters that are scientifically-based and fully reflect site conditions for critical radionuclides,
- Provide accurate models for long-term dose assessments, and
- Provide for cost saving through reduction in unnecessary remediation without commensurate reduction in risk to public or the environment.

<u>Research Goal 2</u> - ***Improved scientific characterization and modeling of radon and its atmospheric dispersion at in-situ mines will***

- Improve measurement and modeling of radon dispersion enabling credible assessments of dose to workers and especially the public. This has the potential to reduce remediation costs and environmental impacts resulting from planned remediation of these sites.

Research Goal 3 - ***Improved techniques to accurately characterize and model subsurface radionuclides in soil and groundwater will***

- Improve dose assessment and guide effective remediation of impacted sites particularly for subsurface characterization of radionuclides in soil and groundwater. Improved characterization technologies for sub-surface soils and groundwater will enable informed and effective remediation of subsurface radionuclides.

Research Goal 4 - ***Development of novel decontamination techniques will***

- Allow precise segregation of materials associated with D&D to be disposed of as clean waste. This will simultaneously save money and fully protect the public and the environment.

Research Goal 5 - ***Development of improved remote handling techniques will***

- Allow more effective D&D of structures, packaging, and safe storage of any highly radioactive materials for waste disposition. For example, research in upfront reactor design, etc., could reduce the amount of highly radioactive materials and reduce radioactive waste at the end of the facility life cycle. Operations in D&D often require handling of highly radioactive materials which require remote handling to ensure safe processing. Many of these tasks are unique and require new engineering solutions.

Research Goal 6 - ***Development of a better understanding of the dose-response of radiation at low doses separately and as a combined total risk posed by mixed wastes containing both radionuclides and hazardous materials will***

- Clarify dose response at low radiation doses including any confounding effects and potential interactions of radiological and chemical exposures from combined risks associated with D&D operations and waste debris. Many materials produced in D&D operations contain both radioactive and hazardous chemicals, yet most exposure assessment models do not assess risk for both simultaneously nor do they include any confounding effects or interactions.

Research Goal 7 - ***Improved techniques for waste volume reduction will***

- Reduce financial costs and save limited space at radioactive waste repositories. There are substantial cost savings that can be realized with fewer environmental impacts through new and improved strategies and technologies for waste reduction.

Research Goal 8 - ***Research in methods for determination of volumetric contamination will***

- Establish effective measurement techniques for radioduclides distributed within materials, which is technically challenging especially for low-energy radiations and heterogeneously distributed radionuclides in the D&D material.

Research Goal 9 - ***Research in methods and technologies for efficient long-term waste disposal of D&D debris will***

- Enable cost effective waste management. This research should also explore approaches for effective public involvement in decision making. Waste disposal improvements are needed in the areas of landfill designs, explorations into waste treatment, and packaging for long-term disposal. Waste disposal costs for radioactive contaminated materials are substantial due to restrictive regulations. Compliance with these regulations requires new and innovated approaches for waste disposal that protects the safety of the public and the environment using science-based approaches.

5.6. Research Goals to Support the Exploration of Space

Objective

Our understanding of the space radiation environment and the risk it poses to long-duration human health remains very limited. A sustained U.S. presence in space is contingent on protecting operational assets from the harsh radiation environment of spaceflight. Energetic cosmic rays can have deleterious effects on human health, critical flight hardware, propulsion and navigation systems. Despite years of manned spaceflight endeavors, there remains a disparity between research results and observed empirical effects seen in human astronaut crews. This can likely be attributed to the numerous factors that limit terrestrial extrapolation of human clinical consequences from varied animal models, and also the complexity of an accurate ground-based analog of the complex space environment. For example, studies on the effects of space radiation generally use mono-energetic beams and acute, single-ion exposures (including protons, lithium, carbon, oxygen, silicon, iron, etc.) instead of the complex energy spectra and diverse ionic composition of the space radiation environment. In addition, a projected, cumulative mission dose is often delivered in one-time, or rapid and sequential, doses delivered to experimental animals. In most cases, these dose-rates are several orders of magnitude higher than actual space environment exposures. Even the use of animal models introduces error, as studies make use of a variety of animal species with differing responses and sensitivity to radiation that may not represent human responses to similar exposures. Further, studies do not challenge multiple organ systems to respond concurrently to the numerous stressors seen in an operational spaceflight scenario. Historical epidemiological studies of humans, which are generally used for correlation of animal and experimental models, include populations such as atomic bomb or nuclear accident survivors exposed to whole-body irradiation at high doses and high dose-rates, limited to scenarios not found in spaceflight. These disparities and numerous other environmental considerations contribute to the large uncertainties in the outcomes of space radiobiology studies and the applicability of such studies for extrapolation and prediction of clinical health outcomes in future spaceflight crews.

Given the intended future of human spaceflight, with efforts by the United States and commercial sectors to rapidly expand the human presence in space, there is a pressing need to predict likely clinical outcomes of interplanetary radiation exposure on future human explorers in order to develop appropriate and effective mitigation strategies. To achieve this goal and contribute to the protection of U.S. assets operating in the space environment, the Health Physics Society and aerospace community must recognize the historical limitations of previous radiation research and how such limitations should be utilized for future research endeavors. We have sought here to identify ways in which these limitations could be addressed for improved understanding and appropriate risk posture regarding future human spaceflight.

Stakeholders

- Commercial spaceflight sector,
- DoD (e.g. Space Force, Air Force Space Command),

- NASA

<u>Research Goal 1</u> – *Clinical outcomes and development of countermeasures*

- Ascertain clinical diagnosis, in humans, attributable to space radiation exposure
- Development of countermeasures, e.g. pharmaceuticals, that can be utilized during spaceflight.
- Individual genetic based risk profiles for accurate implementation of countermeasures

<u>Research Goal 2</u> - *Low dose-rate effects from galactic cosmic ray (GCR) ions.*

- It has long been presumed that exposure to high doses of space radiation will lead to detrimental outcomes. These include cognitive deficits due to radiation induced damage to the central nervous system (CNS), cardiovascular disease (CVD), and late effects cancer outcomes. The presumption of these outcomes, however, is based on highly-acute exposures to animal models. To date, there has been no clinical diagnosis of these in the large population of astronaut and cosmonauts who have flown on missions 4-6 months or longer.

<u>Research Goal 3</u> - *Utilization of human spaceflight data for dose response studies*

- The majority of research utilized for determining the human health risk due to a space radiation exposure utilizes biologic and environmental surrogates that do not resemble either human physiology or the complex GCR spectrum. We now have the benefit of a larger, cumulative astronaut population that has flown in space while exposed to a variety of doses that exceed the identified thresholds for some degenerative and carcinogenic outcomes. The health of these astronauts, including early indicators of disease, is closely monitored by NASA medical and epidemiological resources with yearly medical examinations and careful records of clinical outcomes. This provides critical, real human data that could be used to evaluate the actual long-term health risk of space radiation.

<u>Research Goal 4</u> - *Improved cross-sections and model dynamics of heavy charged particle interactions*

- The application of high-performance computer systems or supercomputers facilitates high-fidelity radiation studies of materials and human health outcomes by utilizing novel numerical methods. Thus, providing a computational alternative of complex dynamics that are otherwise difficult to mimic in a laboratory setting. These techniques are limited to accurate numerical replication of the complex dynamics of heavy-charged particle interactions. Laboratory measurements are needed to validate numerically predicted processes (e.g. fragmentation, progeny generation, etc.), and further develop the computational dynamics associated with particle transport codes.

<u>Research Goal 5</u> - *Shielding optimization and secondary radiation*

- Optimization of shielding protection, for both human and hardware assets, during spaceflight is will allow for efficient vehicle design while ensuring the protection of human health and mission outcomes.
- Utilization of indigenous materials for shielding allows for minimizing launch mass/volume by efficient use of vehicle hardware or planetary body materials for shielding profiles.

Research Goal 6 - ***Improve space environment models (e.g. GCR flux, solar cycle, SPE occurrence/intensity)***

- Improving our understanding of the changing space radiation environment will allow for efficient vehicle shielding design, optimized mission planning and the implementation of countermeasures.

5.7. Radiation Protection Research Needs for National Defense

Objective

National defense encompasses military operations across the globe in support of combat or non-combat operations, and defense support to the civil authorities (DSCA). Operations around the globe have tested military personnel, equipment and doctrine in many environments. The shortfalls have been noted, and new technology considered for enhancing operations. In light of these considerations, the following needs have been identified.

Stakeholders

- Military personnel and supporting staff
- Emergency response personnel
- General public
- Federal, State, Local, Territorial and Tribal Government
- Medical personnel

Research Goal 1- ***Improved radiation transport codes that allow incorporation of CAD data***

- Improve fidelity and understanding of protection factors for buildings and vehicles related to photons and neutrons
- Determine and refine secondary activation in vehicles, buildings, and other platforms or materials.

Research Goal 2- ***Urban plume modeling***

- Develop urban computation fluid dynamic modelling to improve understanding of radiation environment in a contaminated city, including the effects of man-made structures.
- Improvement of 3D models for plume modeling.
    - Incorporate the effect of weather, specifically precipitation

Research Goal 3- ***Biodosimetry for rapid triage***

- Development of rapid biodosimetry, critical for sorting casualties and managing critical medical resources
- Novel detection materials need to be investigated to determine a rapid, sufficiently accurate method of determining dose
- Improvement of biodosimetry methods enabling determination of both stochastic and non-stochastic effects, enhancing both near term treatment and long-term management of injury/disease

<u>Research Goal 4</u>- *Dosimetry models for working animals (dogs/seals/dolphins/horses/mules)*

- Develop/improve dose models for working animal. The military considers these important, costly and low-density assets critical to support operations.
    - Investigate and refine unique elements associated with animal dosimetry, to include bio-kinetics, available protection limited by need for smell, differing treatment and prophylaxis, geometry and physical conformation.
- Identify and determine efficacy of treatment and prophylaxis agents for working animals, along with dosing guidelines, to preserve these critical resources.

<u>Research Goal 5</u>- *Personnel performance degradation, with consideration of medical countermeasures*

- Develop and refine understanding of performance degradation following administration of treatment/prophylaxis agents (i.e., Neupogen and DTPA)?
- Charts for combat effectiveness need to be updated based on new information, to include:
    - Anti-emetic drugs (Zofran etc.)
    - LD_{50} with medical intervention, given advances in treatment regimes
    - Refine radiation effects models, incorporating unit specific variables
        - Output includes different exposure scenarios, morbidity, mortality, time sensitivity, and long-term effects.

<u>Research Goal 6</u>- *Development of coatings that inhibit/indicate contamination due to fallout*

- Development of anti-contamination coatings and materials for application on surfaces
    - Consider exterior, interior, engines, harsh environments
    - Development of ablative coatings that can be peeled off to remove contamination
- Development of novel materials that visually indicate contaminated surfaces to which they are applied.
- Related: Develop contamination assessment methodology/model on large equipment (without taking equipment apart)

<u>Research Goal 7</u>- *Portable, rugged detection instrumentation*

- Improved Neutron detection (non-Li-6)
    - Includes consideration of all potential neutron energies
    - Investigate sodium based nanodosimeters
    - Investigate solid state silicon
- Dosimeter sensitive to all radiation types (excluding alpha radiation)
    - Considerations related to Infrastructural threshold of active versus passive
    - Refinement for use as dose of record
- Development/refinement of smaller (mass and volume), less expensive and improved performance radiation detection instrumentation
    - Incorporate capability to quantify dose rate, identify source radioisotope with improved efficiency and accuracy.
    - Lower power requirements to enable longer operational times
        - Incorporate common battery-type compatibility to ease logistics burden

<u>Research Goal 8</u>- *Unmanned detection robots*

- Develop unmanned light weight airborne radiation detection systems, especially useful for areas in which there are multiple hazards (CBRN)
    - Incorporate data transmission capability, with the following constraints:
        - Data security
        - Prevent transmission detection
        - Robust in harsh environments
    - Develop gamma imaging/mapping for indoor surveys
    - Incorporate capability to evaluate contamination of ventilation equipment

<u>Research Goal 9</u>- *Hardening of electronics against radiation damage*

- Development of methods/mechanisms/materials to harden modern electronics to enable operation in the aftermath of a nuclear detonation (Note: modern electronics including integrated circuits, are particularly vulnerable to neutron damage).

<u>Research Goal 10</u>- *Novel materials*

- Development of Smart Fabrics that give indication of the radiation environment
- Consideration of organic photonics and electronics
- Development of novel detection material capable of integration into the exterior of a vehicle (ground, air, naval)

<u>Research Goal 11</u>- *Determination of protection factors (PFs) for modern combat and non-combat vehicles and structures built using various designs and materials.*

- Develop computer model to support determination of PFs for military vehicles
    - Improve Exposure Guidelines Technical manual.
        - Accommodates personnel and location variables,
        - Include aircraft and water craft
    - Develop tool to convert CAD files for military vehicles to allow PF determination, conjunction with radiation transport code
    - Improve understanding of building materials with respect to radiation attenuation.
    - Incorporate activation of materials in models to improve understanding of nuclear weapons effects

5.8. Emergency Response Research Needs

Objective

Emergency response encompasses elements related to the environment, people (emergency responders, decision makers, the general public), technical support, communications, detection and dose assessment, tactical and operational guidance, and many other related and supporting tools, functions and variables. Appreciating this complexity, emergency response research needs fall under five broad categories, with individual lines of research specified as follows:

Stakeholders
- Military personnel and supporting staff
- Emergency response personnel
- Nuclear reactor operators
- General public
- Health effects modelers
- Risk Managers
- Government personnel

Research Goal 1- *Improved Modelling/Prediction Methods*
- Develop improved water models, particularly fresh water
- Develop improved environmental transport models
- Develop models to determine time delimited migration of contaminants following deposition
- Increase understanding of atmospheric dispersion modeling uncertainty
- Develop logistical models for prediction of resources and medical supplies needed for response
- Develop and refine population modeling, to include dispersion, evacuation and patient tracking
- Develop and disseminate common protocols for collecting and storing bio-specimens

Research Goal 2- *Improved Measurement of radiation/radioactive materials*
- Develop a network of bio-dosimetry laboratories, including common SOPs and standardized calibration curves
- Develop methods for rapid assessment of strontium release
- Develop characterization methods for a continuous release
- Develop high throughput and field hardened analytical methods and instrumentation

Research Goal 3- *Improved methods in support of analysis and interpretation*
- Develop more efficient sample tracking methods
- Develop improved bioassay for alpha emitters

Research Goal 4- Enhanced *Communication capabilities*
- Develop standardized methods to communicate threat-based PPE requirements
- Develop a standardized and broadly distributed lexicon for radiological incident communications
- Develop adequate and effective tools to support decision-making during and following an incident

Research Goal 5- *Develop Health and Safety Enablers*
- Develop training and readiness enhancement tools for health care providers
- Develop assay for low-energy radionuclides
- Develop rubric for determining PPE based on geographic location relative to the incident

5.9. Research Needs for Predicting Fate and Effects of Radionuclides in the Environment

Objective
Radiation protection from radionuclides dispersed in the environment is essential for the development of effective risk predictions and remediation strategies. The HPS supports research that enables accurate modeling of radionuclides in the environment through the following.

Stakeholders
- General Public
- Regulators
- Emergency response personnel
- Personnel engaged in decommissioning and decontamination, including environmental remediation
- Radioecologists

Research Goal 1- ***Radionuclide fate and transport modeling supported by appropriate field research***
- Improve model robustness by validating under, or offering adjustments for, new conditions,
- Validate laboratory results, and inform how they can be extrapolated to larger scales, and
- Develop and integrate methods for more cost-effective management of risk.

Research Goal 2- ***Incorporate culturally relevant activities in pathway models***
- Develop and incorporate a broader, more realistic array of culturally relevant population activities into risk assessments, enabling implementation of more suitable and cost-effective interventions.

Research Goal 3- ***Identify bioindicator species within each climatological area***
- Enable utilization of such sentinel species to discern the movement of radioactive pollutants in the environment,
- Assist in validation of transport modeling, and
- Identify presence of nuclear-related activities.

Research Goal 4- ***Identify and increase understanding of confounding effects due to chemical and physical stressors in conjunction with radiological exposures***
- Improve understanding and attribution of health effects, and
- Enable determination and assessment of the true effect of the contaminant of concern.

Research Goal 5- ***Increase understanding of linking mechanisms of radiation interaction to effects across multiple levels of biological organization***
- Improve understanding of risk due to exposures at low dose,
- Develop methods for assessing endpoints at a scale relevant to risk assessment and management,
- Develop method to reconcile laboratory and field results.

6. RESEARCH SYNERGIES

Research is a cornerstone of effective policy development and implementation. It provides the scientific foundation for sound, evidence-based judgements. Of course, research is also informed by policy, as we seek to develop creative and comprehensive solutions to problems relevant to stakeholders' missions or experience. Research also contributes to science communication and outreach to help the public develop informed opinions, which, when combined with their values and priorities, are a significant factor in policy development. In short:

- Research is necessary for the education and training of students to ensure an adequate supply of qualified workers.
- Research findings are important in communicating with the public to encourage a practical radiation protection culture and the ability of the public to make informed decisions with respect to radiation and related activities.
- Research informs evidence-based policy for the benefit of all.
- Research is informed by scientific knowledge gaps and stakeholder experiences.

Figure 1. Broader outcomes of funded research.

Considering the interconnectedness of research within the fabric of society, we realize that research informs and is informed by that societal context and its needs. Within this context, we recognize the synergistic and collaborative nature of research, especially important as our knowledge of individual disciplines broadens and deepens. Given this understanding, it is not surprising that within a given discipline, there are also synergies and opportunities for collaboration to enable further depth and breadth of understanding. Within the field of health physics, there is a general consensus that the major research needs can be categorized broadly into nine (9) research areas. Within these 9 areas are specific research topics or goals, but despite this specificity, most of these research topics are interrelated and support multiple research areas, with some of these connections shown in the figure below.

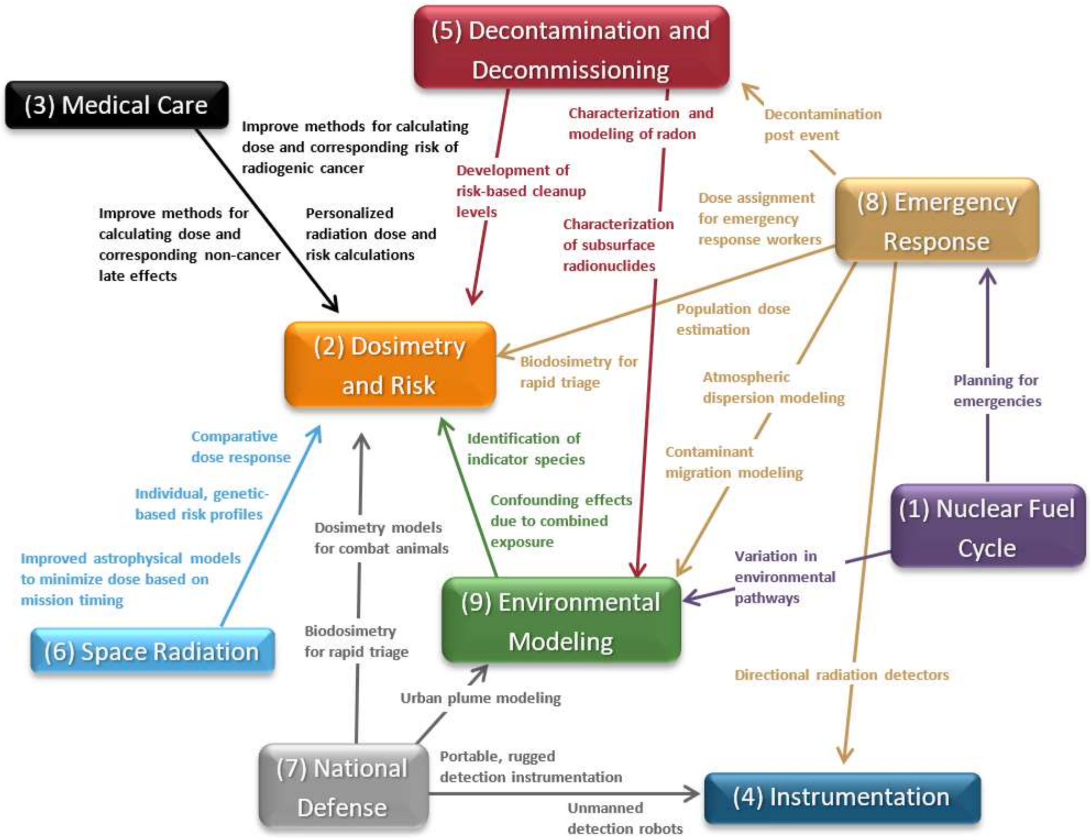

Figure 2. Representative research commonalities.

For example, within the "Decontamination and Decommissioning" research area, there is a heavy focus on developing techniques and models that will improve cost-effectiveness of remediation strategies. This is also a cornerstone of the "Environmental Modeling" research area. Although the applications are slightly different, each research area involves elements associated with improving site-specific understanding, which in turn will enable improved risk assessment and management. The "Emergency Response" research area also includes topics related to improved transport models, specifically atmospheric dispersion and contaminant migration. The "Dosimetry and Risk" research area has relevance to nearly all of the other research areas, with several common topics. For example, biodosimetry for rapid triage is a research need within both "Emergency Response" and "National Defense," and individualized dosimetric models with improved methods for calculating risk is common to both "Medical Physics" and "Space Radiation" research areas.

In leveraging these synergies, we can achieve more with limited resources. If we ensure that researchers are communicating, we can limit redundancy and increase productivity. We can create the conditions where one line of research is furthering several others, ensuring knowledge gaps and needs are fulfilled faster and with fewer resources. Communication and data sharing between research groups is a critical enabler and should be highly encouraged. In addition, funding agencies should recognize that their funding decisions have a broader impact on the research landscape than in just the program being considered for funding.

7. RESEARCH PRIORITIZATION

Rather than assigning priority without regard to context, the Task Force decided that each involved organization or individual should make these determinations in the context of their unique circumstances. We appreciate that the various funding and research institutions will have contextually dependent priorities based on the dictates of their missions and responsibilities, while being constrained by available resources (time, money, staff, facilities, etc.) and formal authorities and directives. The Task force would like to recommend that, in the course of establishing priorities, due consideration to the following principles is integrated into the prioritization calculus:

- Magnitude of risk reduction (e.g., lives saved or cancers averted) Risk reduction is getting at buying down risk in the most efficient ways. Resources expended should achieve the largest reductions in risk possible.
- Potential resource savings (time, money, materiel; i.e., no longer having to reduce residual contamination to a level approaching background). Monetary savings is getting at the cost of conducting contamination/dose reduction across individuals and populations, both with regard to safety measures implemented in design, and exposure reduction upon decommissioning, or post-incident.
- Degree of operational impact- how methods and equipment can make the 'job' quicker, easier, or more precise upon application. It also includes those impacts that will increase the performance and endurance of personnel and/or equipment in the defined operational context.
- Clinical impact (dose estimation speed and refinement; prophylaxis and treatment) Clinical impact refers to effectiveness of prophylaxis, and treatment, accuracy and precision of dose delivery, maximizing diagnostic information with minimization of dose.
- Decision making impact (speed, accuracy) Decision making impact gets to how the technology or novel methods improve the decision cycle in terms of time and certainty.
- Reduction of confounding effects Reduction of confounding effects helps to isolate risk associated with given insult, allowing more effective management in a holistic context.
- Synergy of research with other areas of investigation, i.e., more wide-ranging questions often inform more than one area of interest, and often create opportunities for additional and/or cooperative investigation.

8. SUMMARY

The Task force has broken down research needs into nine broad areas, as follows:

- Nuclear Fuel Cycle and Nuclear Power Production
- Radiation Protection through Improved Estimates of Radiation Effects/Risk at Low Doses
- Use of Radiation for Medical Care
- Improved Measurement of Radiation through Instrument Developments
- Decontamination and Decommissioning of Nuclear Facilities
- Exploration of Space
- National Defense
- Emergency Response to Nuclear Events
- Prediction of Fate and Effects of Radionuclides in the Environment

Each area has a number of associated research goals with supporting sub-goals. This enumeration is intended to provide the research direction needed to fill gaps in our knowledge, and to provide the seeds of ideas for relevant research. The idea of research synergy is presented to encourage collaborative discussions, thought, and activities that cut across specialties, with the expectation that the collaborative effort will multiply the research effort, producing better and more abundant results with smaller input of resources, across multiple disciplines. The Task Force concludes with a number of recommended considerations for prioritizing research efforts, designed to produce more relevant results while efficiently utilizing limited resources within the context of each research institution.

This document is a distillation of the work of many, to include all those involved in the initial workshop, the various Task Force members and the Health Physics Society leadership. The amount of experience and expertise across the radiation safety community brought to bear on this issue is considerable, and reflects the importance the Health Physics Society places on the research enterprise. It is our intent that this document provides a springboard for a more comprehensive evaluation of research needs, leveraging synergy and the prioritization principles outlined. This and following efforts are critical to broadening and deepening our understanding of the nature of radiation and radioactive materials, maintaining an educated workforce, good stewardship of limited resources, and prudently managing associated risk. It is also intended that this document provide the basis for collaboration with our sister societies that have overlapping interest in radiation and radioactivity.

APPENDIX A: ABBREVIATIONS AND ACRONYMS

ALLIANCE	European Radioecology Alliance
ATF	accident tolerant fuel
ANS	American Nuclear Society
CAD	computer aided design
CBRN	chemical, biological, radiological, nuclear
CONCERT	European Joint Programme for the Integration of Radiation Protection Research
CRPK	Center for Radiation Protection Knowledge
CNS	central nervous system
CT	computed tomography
CVD	cardiovascular disease
D&D	decontamination and decommissioning
DOE	U.S. Department of Energy
DHS	U.S. Department of Homeland Security
DoD	U.S. Department of Defense
DSCA	defense support to the civil authorities
DTPA	diethylenetriamine pentaacetic acid
EPA	U.S. Environmental Protection Agency
EURADOS	European Radiation Dosimetry Group
FDA	U.S. Food and Drug Administration
FEMA	Federal Emergency Management Agency
GCR	galactic cosmic radiation
HPS	Health Physics Society
HTGR	high-temperature gas-cooled reactor
LD	lethal dose
MASH	Monte Carlo Adjoint Shielding Code System
MCNP	Monte Carlo N-Particle
MELODI	Multidisciplinary European Low Dose Initiative
MSR	molten salt reactor
mSv	milli-sievert; SI unit of dose equivalent
NASA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organization
NCRP	National Council on Radiation Protection and Measurements
NERIS	European Platform on Preparedness for Nuclear and Radiological Emergency Response and Recovery
NIST	National Institute of Standards and Technology
OPERRA	Open Projects for European Radiation Research Area
ORAU	Oak Ridge Associated Universities
ORNL	Oak Ridge National Laboratory
R&D	research and development
rad	radiation absorbed dose; traditional unit of absorbed dose
rem	roentgen equivalent man; the traditional unit of dose equivalent
RPRN	Radiation Protection Research Needs
SFR	sodium fast reactor
SI	Systeme Internationale, or metric system of measure
SMR	small modular reactor
SPE	solar particle event
SRA	Strategic research agenda
Sv	Sievert; SI unit of dose equivalent

TENORM	technologically enhanced naturally occurring radioactive material
USG	United States Government
WARP	Where Are the Radiation Professionals

APPENDIX B: DEFINITION OF TERMS

(Adapted from Radiation Emergencies, Glossary of Radiological Terms, https://emergency.cdc.gov/radiation/pdf/glossary.pdf, accessed 20 Jul 2021)

Absolute risk: the proportion of a population expected to get a disease over a specified time period. See also risk, relative risk.

Absorbed dose: the amount of energy deposited by ionizing radiation in a unit mass of tissue. It is expressed in units of joule per kilogram (J/kg), and called "gray" (Gy).

Activity (radioactivity): the rate of decay of radioactive material expressed as the number of atoms breaking down per second measured in units called becquerels or curies.

Acute exposure: an exposure to radiation that occurred in a matter of minutes rather than in longer, continuing exposure over a period of time. See also chronic exposure, exposure, fractionated exposure.

Acute Radiation Syndrome (ARS): a serious illness caused by receiving a dose greater than 50 rads of penetrating radiation to the body in a short time (usually minutes). The earliest symptoms are nausea, fatigue, vomiting, and diarrhea. Hair loss, bleeding, swelling of the mouth and throat, and general loss of energy may follow. If the exposure has been approximately 1,000 rads or more, death may occur within 2 – 4 weeks.

Air burst: a nuclear weapon explosion that is high enough in the air to keep the fireball from touching the ground. Because the fireball does not reach the ground and does not pick up any surface material, the radioactivity in the fallout from an air burst is relatively insignificant compared with a surface burst.

Alpha particle: the nucleus of a helium atom, made up of two neutrons and two protons with a charge of +2. Certain radioactive nuclei emit alpha particles. Alpha particles generally carry more energy than gamma or beta particles, and deposit that energy very quickly while passing through tissue. Alpha particles can be stopped by a thin layer of light material, such as a sheet of paper, and cannot penetrate the outer, dead layer of skin. Therefore, they do not damage living tissue when outside the body. When alpha-emitting atoms are inhaled or swallowed, however, they are especially damaging because they transfer relatively large amounts of ionizing energy to living cells. See also beta particle, gamma ray, neutron, x-ray.

Ambient air: the air that surrounds us.

Americium (Am): a silvery metal; it is a man-made element whose isotopes Am-237 through Am-246 are all radioactive. Am-241 is formed spontaneously by the beta decay of plutonium-241. Trace quantities of americium are widely used in smoke detectors, and as neutron sources in neutron moisture gauges.

Atom: the smallest particle of an element that can enter into a chemical reaction.

Atomic number: the total number of protons in the nucleus of an atom.

Atomic mass unit (amu): 1 amu is equal to one twelfth of the mass of a carbon-12 atom.

Atomic mass number: the total number of protons and neutrons in the nucleus of an atom.

Atomic weight: the mass of an atom, expressed in atomic mass units. For example, the atomic number of helium-4 is 2, the atomic mass is 4, and the atomic weight is 4.00026.

Background radiation: ionizing radiation from natural sources, such as terrestrial radiation due to radionuclides in the soil or cosmic radiation originating in outer space.

Becquerel (Bq): the amount of a radioactive material that will undergo one decay (disintegration) per second.

Beta particles: electrons ejected from the nucleus of a decaying atom. Although they can be stopped by a thin sheet of aluminum, beta particles can penetrate the dead skin layer, potentially causing burns. They can pose a serious direct or external radiation threat and can be lethal depending on the amount received. They also pose a serious internal radiation threat if beta-emitting atoms are ingested or inhaled. See also alpha particle, gamma ray, neutron, x-ray.

Bioassay: an assessment of radioactive materials that may be present inside a person's body through analysis of the person's blood, urine, feces, or sweat.

Biological Effects of Ionizing Radiation (BEIR) Reports: reports of the National Research Council's committee on the Biological Effects of Ionizing Radiation.

Biological half-life: the time required for one half of the amount of a substance, such as a radionuclide, to be expelled from the body by natural metabolic processes, not counting radioactive decay, once it has been taken in through inhalation, ingestion, or absorption. See also radioactive half-life, effective half-life.

Carcinogen: a cancer-causing substance.

Chain reaction: a process that initiates its own repetition. In a fission chain reaction, a fissile nucleus absorbs a neutron and fissions (splits) spontaneously, releasing additional neutrons. These, in turn, can be absorbed by other fissile nuclei, releasing still more neutrons. A fission chain reaction is self-sustaining when the number of neutrons released in a given time equals or exceeds the number of neutrons lost by absorption in non-fissile material or by escape from the system.

Chronic exposure: exposure to a substance over a long period of time, possibly resulting in adverse health effects. See also acute exposure, fractionated exposure.

Cobalt (Co): gray, hard, magnetic, and somewhat malleable metal. Cobalt is relatively rare and generally obtained as a byproduct of other metals, such as copper. Its most common radioisotope, cobalt-60 (Co-60), is used in radiography and medical applications. Cobalt-60 emits beta particles and gamma rays during radioactive decay.

Collective dose: the estimated dose for an area or region multiplied by the estimated population in that area or region.

Committed dose: a dose that accounts for continuing exposures expected to be received over a long period of time (such as 30, 50, or 70 years) from radioactive materials that were deposited inside the body.

Concentration: the ratio of the amount of a specific substance in a given volume or mass of solution to the mass or volume of solvent.

Conference of Radiation Control Program Directors (CRCPD): an organization whose members represent state radiation protection programs.

Contamination (radioactive): the deposition of unwanted radioactive material on the surfaces of structures, areas, objects, or people where it may be external or internal. See also decontamination.

Cosmic radiation: radiation produced in outer space when heavy particles from other galaxies (nuclei of all known natural elements) bombard the earth. See also background radiation, terrestrial radiation.

Criticality: a fission process where the neutron production rate equals the neutron loss rate to absorption or leakage. A nuclear reactor is "critical" when it is operating.

Critical mass: the minimum amount of fissile material that can achieve a self-sustaining nuclear chain reaction.

Cumulative dose: the total dose resulting from repeated or continuous exposures of the same portion of the body, or of the whole body, to ionizing radiation.

Curie (Ci): the traditional measure of radioactivity based on the observed decay rate of 1 gram of radium. One curie of radioactive material will have 37 billion disintegrations in 1 second.

Cutaneous Radiation Syndrome (CRS): the complex syndrome resulting from radiation exposure of more than 200 rads to the skin. The immediate effects can be reddening and swelling of the exposed area (like a severe burn), blisters, ulcers on the skin, hair loss, and severe pain. Very large doses can result in permanent hair loss, scarring, altered skin color, deterioration of the affected body part, and death of the affected tissue (requiring surgery).

Decay chain (decay series): the series of decays that certain radioisotopes go through before reaching a stable form. For example, the decay chain that begins with uranium-238 (U-238) ends in lead-206 (Pb-206), after forming isotopes, such as uranium-234 (U-234), thorium-230 (Th-230), radium-226 (Ra-226), and radon-222 (Rn-222).

Decay constant: the fraction of a number of atoms of a radioactive nuclide that disintegrates in a unit of time. The decay constant is inversely proportional to the radioactive half-life.

Decay products (or daughter products): the isotopes or elements formed and the particles and high-energy electromagnetic radiation emitted by the nuclei of radionuclides during radioactive decay. Also known as "decay chain products" or "progeny" (the isotopes and elements). A decay product may be either radioactive or stable.

Decay, radioactive: disintegration of the nucleus of an unstable atom by the release of radiation.

Decontamination: the reduction or removal of radioactive contamination from a structure, object, or person.

Depleted uranium: uranium containing less than 0.7% uranium-235, the amount found in natural uranium. See also enriched uranium. Deposition density: the activity of a radionuclide per unit area of ground. Reported as becquerels per square meter or curies per square meter.

Deterministic effects: effects that can be related directly to the radiation dose received. The severity increases as the dose increases. A deterministic effect typically has a threshold below which the effect will not occur. See also stochastic effect, non-stochastic effect.

Deuterium: a non-radioactive isotope of the hydrogen atom that contains a neutron in its nucleus in addition to the one proton normally seen in hydrogen. A deuterium atom is twice as heavy as normal hydrogen. See also tritium.

Dirty bomb: a device designed to spread radioactive material by conventional explosives when the bomb explodes. A dirty bomb kills or injures people through the initial blast of the conventional explosive and spreads radioactive contamination over possibly a large area—hence the term "dirty." Such bombs could be miniature devices or large truck bombs. A dirty bomb is much simpler to make than a true nuclear weapon. See also radiological dispersal device.

Dose (radiation): radiation absorbed by person's body. Several different terms describe radiation dose.

Dose coefficient: the factor used to convert radionuclide intake to dose. Usually expressed as dose per unit intake (e.g., sieverts per becquerel).

Dose equivalent: a quantity used in radiation protection to place all radiation on a common scale for calculating tissue damage. Dose equivalent is the absorbed dose in grays times the quality factor. The quality factor accounts for differences in radiation effects caused by different types of ionizing radiation. Some radiation, including alpha particles, causes a greater amount of damage per unit of absorbed dose than other radiation. The sievert (Sv) is the unit used to measure dose equivalent.

Dose rate: the radiation dose delivered per unit of time.

Dose reconstruction: a scientific study that estimates doses to people from releases of radioactivity or other pollutants. The dose is reconstructed by determining the amount of material released, the way people came in contact with it, and the amount they absorbed.

Dosimeter: a small portable instrument (such as a film badge, thermoluminescent dosimeter [TLD], or pocket dosimeter) for measuring and recording the total accumulated dose of ionizing radiation a person receives.

Dosimetry: assessment (by measurement or calculation) of radiation dose.

Effective dose: a dosimetric quantity useful for comparing the overall health effects of irradiation of the whole body. It takes into account the absorbed doses received by various organs and tissues and weighs them according to present knowledge of the sensitivity of each organ to radiation. It also accounts for the type of radiation and the potential for each type to inflict biologic damage. The effective dose is used, for example, to compare the overall health detriments of different radionuclides in a given mix. The unit of effective dose is the sievert (Sv); 1 Sv = 1 J/kg.

Effective half-life: the time required for the amount of a radionuclide deposited in a living organism to be diminished by 50% as a result of the combined action of radioactive decay and biologic elimination. See also biological half-life, decay constant, radioactive half-life.

Electron: an elementary particle with a negative electrical charge and a mass 1/1837 that of the proton. Electrons surround the nucleus of an atom because of the attraction between their negative charge and the positive charge of the nucleus. A stable atom will have as many electrons as it has protons. The number of electrons that orbit an atom determine its chemical properties. See also neutron.

Electron volt (eV): a unit of energy equivalent to the amount of energy gained by an electron when it passes from a point of low potential to a point one volt higher in potential.

Element: 1) all isotopes of an atom that contain the same number of protons. For example, the element uranium has 92 protons, and the different isotopes of this element may contain 134 to 148 neutrons. 2) In a reactor, a fuel element is a metal rod containing the fissile material.

Enriched uranium: uranium in which the proportion of the isotope uranium-235 has been increased by removing uranium-238 mechanically. See also depleted uranium.

Epidemiology: the study of the distribution and determinants of health-related states or events in specified populations; and the application of this study to the control of health problems.

Exposure (radiation): a measure of ionization in air caused by x-rays or gamma rays only. The unit of exposure most often used is the roentgen. See also contamination.

Exposure pathway: a route by which a radionuclide or other toxic material can enter the body. The main exposure routes are inhalation, ingestion, absorption through the skin, and entry through a cut or wound in the skin.

Exposure rate: a measure of the ionization produced in air by x-rays or gamma rays per unit of time (frequently expressed in roentgens per hour). External exposure: exposure to radiation outside of the body.

Fallout, nuclear: minute particles of radioactive debris that descend slowly from the atmosphere after a nuclear explosion.

Fissile material: any material in which neutrons can cause a fission reaction. The three primary fissile materials are uranium-233, uranium-235, and plutonium-239.

Fission (fissioning): the splitting of a nucleus into at least two other nuclei that releases a large amount of energy. Two or three neutrons are usually released during this transformation. See also fusion.

Fractionated exposure: exposure to radiation that occurs in several small acute exposures, rather than continuously as in a chronic exposure.

Fusion: a reaction in which at least one heavier, more stable nucleus is produced from two lighter, less stable nuclei. Reactions of this type are responsible for the release of energy in stars or in thermonuclear weapons.

Gamma rays: high-energy electromagnetic radiation emitted by certain radionuclides when their nuclei transition from a higher to a lower energy state. These rays have high energy and a short wave length. All gamma rays emitted from a given isotope have the same energy, a characteristic that enables scientists to identify which gamma emitters are present in a sample. Gamma rays penetrate tissue farther than do beta or alpha particles, but leave a lower concentration of ions in their path to potentially cause cell damage. Gamma rays are very similar to x-rays. See also neutron.

Geiger counter: a radiation detection and measuring instrument consisting of a gas-filled tube containing electrodes, between which an electrical voltage but no current flows. When ionizing radiation passes through the tube, a short, intense pulse of current passes from the negative electrode to the positive electrode and is measured or counted. The number of pulses per second measures the intensity of the radiation field. Geiger counters are the most commonly used portable radiation detection instruments.

Genetic effects: hereditary effects (mutations) that can be passed on through reproduction because of changes in sperm or ova. See also teratogenic effects, somatic effects.

Gray (Gy): a unit of measurement for absorbed dose. It measures the amount of energy absorbed in a material. The unit Gy can be used for any type of radiation, but it does not describe the biological effects of the different radiations.

Half-life: the time any substance takes to decay by half of its original amount. See also biological half-life, decay constant, effective half-life, radioactive half-life.

Health physics: a scientific field that focuses on protection of humans and the environment from radiation. Health physics uses physics, biology, chemistry, statistics, and electronic instrumentation to help protect individuals from any damaging effects of radiation.

High-level radioactive waste: the radioactive material resulting from spent nuclear fuel reprocessing. This can include liquid waste directly produced in reprocessing or any solid material derived from the liquid wastes having a sufficient concentration of fission products. Other radioactive materials can be designated as high-level waste, if they require permanent isolation. This determination is made by the U.S. Nuclear Regulatory Commission on the basis of criteria established in U.S. law. See also low-level waste, transuranic waste.

Hot spot: any place where the level of radioactive contamination is considerably greater than the area around it.

Ingestion: 1) the act of swallowing; 2) in the case of radionuclides or chemicals, swallowing radionuclides or chemicals by eating or drinking.

Inhalation: 1) the act of breathing in; 2) in the case of radionuclides or chemicals, breathing in radionuclides or chemicals.

Internal exposure: exposure to radioactive material taken into the body.

Iodine: a nonmetallic solid element. There are both radioactive and non-radioactive isotopes of iodine. Radioactive isotopes of iodine are widely used in medical applications. Radioactive iodine is a fission product and is the largest contributor to people's radiation dose after an accident at a nuclear reactor. Ion: an atom that has fewer or more electrons than it has protons causing it to have an electrical charge and, therefore, be chemically reactive.

Ionization: the process of adding one or more electrons to, or removing one or more electrons from, atoms or molecules, thereby creating ions. High temperatures, electrical discharges, or nuclear radiation can cause ionization.

Ionizing radiation: any radiation capable of displacing electrons from atoms, thereby producing ions. High doses of ionizing radiation may produce severe skin or tissue damage. See also alpha particle, beta particle, gamma ray, neutron, x-ray. Irradiation: exposure to radiation.

Isotope: a nuclide of an element having the same number of protons but a different number of neutrons.

Kiloton (kt): the energy of an explosion that is equivalent to an explosion of 1,000 tons of TNT. One kiloton equals 1 trillion (1012) calories. See also megaton.

Latent period: the time between exposure to a toxic material and the appearance of a resultant health effect. Lead (Pb): a heavy metal. Several isotopes of lead, such as Pb-210 which emits beta radiation, are in the uranium decay chain.

Lead Federal Agency (LFA): the federal agency that leads and coordinates the emergency response activities of other federal agencies during a nuclear emergency. After a nuclear emergency, the Federal Radiological Emergency Response Plan (FRERP) will determine which federal agency will be the LFA.

Local radiation injury (LRI): acute radiation exposure (more than 1,000 rads) to a small, localized part of the body. Most local radiation injuries do not cause death. However, if the exposure is from penetrating radiation (neutrons, x-rays, or gamma rays), internal organs may be damaged and some symptoms of acute radiation syndrome (ARS), including death, may occur. Local radiation injury invariably involves skin damage, and a skin graft or other surgery may be required.

Low-level waste (LLW): radioactively contaminated industrial or research waste such as paper, rags, plastic bags, medical waste, and water-treatment residues. It is waste that does not meet the criteria for any of three other categories of radioactive waste: spent nuclear fuel and high-level radioactive waste; transuranic radioactive waste; or uranium mill tailings. Its categorization does not depend on the level of radioactivity it contains.

Megaton (Mt): the energy of an explosion that is equivalent to an explosion of 1 million tons of TNT. One megaton is equal to a quintillion (1018) calories. See also kiloton.

Molecule: a combination of two or more atoms that are chemically bonded. A molecule is the smallest unit of a compound that can exist by itself and retain all of its chemical properties.

Neoplastic: pertaining to the pathologic process resulting in the formation and growth of an abnormal mass of tissue.

Neutron: a small atomic particle possessing no electrical charge typically found within an atom's nucleus. Neutrons are, as the name implies, neutral in their charge. That is, they have neither a positive nor a negative charge. A neutron has about the same mass as a proton. See also alpha particle, beta particle, gamma ray, nucleon, x-ray.

Non-ionizing radiation: radiation that has lower energy levels and longer wavelengths than ionizing radiation. It is not strong enough to affect the structure of atoms it contacts but is strong enough to heat tissue and can cause harmful biological effects. Examples include radio waves, microwaves, visible light, and infrared from a heat lamp.

Non-stochastic effects: effects that can be related directly to the radiation dose received. The effect is more severe with a higher dose. It typically has a threshold, below which the effect will not occur. These are sometimes called deterministic effects. For example, a skin burn from radiation is a non-stochastic effect that worsens as the radiation dose increases. See also stochastic effects.

Nuclear energy: the heat energy produced by the process of nuclear fission within a nuclear reactor or by radioactive decay.

Nuclear fuel cycle: the steps involved in supplying fuel for nuclear power plants. It can include mining, milling, isotopic enrichment, fabrication of fuel elements, use in reactors, chemical reprocessing to recover the fissile material remaining in the spent fuel, re-enrichment of the fuel material refabrication into new fuel elements, and waste disposal.

Nuclear tracers: radioisotopes that give doctors the ability to "look" inside the body and observe soft tissues and organs, in a manner similar to the way x-rays provide images of bones. A radioactive tracer is chemically attached to a compound that will concentrate naturally in an organ or tissue so that an image can be taken.

Nucleon: a proton or a neutron; a constituent of the nucleus of an atom.

Nucleus: the central part of an atom that contains protons and neutrons. The nucleus is the heaviest part of the atom.

Nuclide: a general term applicable to all atomic forms of an element. Nuclides are characterized by the number of protons and neutrons in the nucleus, as well as by the amount of energy contained within the atom.

Pathways: the routes by which people are exposed to radiation or other contaminants. The three basic pathways are inhalation, ingestion, and direct external exposure. See also exposure pathway.

Penetrating radiation: radiation that can penetrate the skin and reach internal organs and tissues. Photons (gamma rays and x-rays), neutrons, and protons are penetrating radiations. However, alpha particles and all but extremely high-energy beta particles are not considered penetrating radiation.

Photon: discrete "packet" of pure electromagnetic energy. Photons have no mass and travel at the speed of light. The term "photon" was developed to describe energy when it acts like a particle (causing interactions at the molecular or atomic level), rather than a wave. Gamma rays and x-rays are photons.

Pitchblende: a brown to black mineral that has a distinctive luster. It consists mainly of uraninite (UO2), but also contains radium (Ra). It is the main source of uranium (U) ore.

Plume: the material spreading from a particular source and traveling through environmental media, such as air or ground water. For example, a plume could describe the dispersal of particles, gases, vapors, and aerosols in the atmosphere, or the movement of contamination through an aquifer (For example, dilution, mixing, or adsorption onto soil).

Plutonium (Pu): a heavy, man-made, radioactive metallic element. The most important isotope is Pu-239, which has a half-life of 24,000 years. Pu-239 can be used in reactor fuel and is the primary isotope in weapons. One kilogram is equivalent to about 22 million kilowatt-hours of heat energy. The complete detonation of a kilogram of plutonium produces an explosion equal to about 20,000 tons of chemical explosive. All isotopes of plutonium are readily absorbed by the bones and can be lethal depending on the dose and exposure time.

Polonium (Po): a radioactive chemical element and a product of radium (Ra) decay. Polonium is found in uranium (U) ores.

Prenatal radiation exposure: radiation exposure to an embryo or fetus while it is still in its mother's womb. At certain stages of the pregnancy, the fetus is particularly sensitive to radiation and the health consequences could be severe above 5 rads, especially to brain function.

Protective Action Guide (PAG): a guide that tells state and local authorities at what projected dose they should take action to protect people from exposure to unplanned releases of radioactive material into the environment.

Proton: a small atomic particle, typically found within an atom's nucleus, that possesses a positive electrical charge. Even though protons and neutrons are about 2,000 times heavier than electrons, they are tiny. The number of protons is unique for each chemical element. See also nucleon.

Quality factor (Q): the factor by which the absorbed dose (rad or gray) is multiplied to obtain a quantity that expresses, on a common scale for all ionizing radiation, the biological damage (rem) to an exposed person. It is used because some types of radiation, such as alpha particles, are more biologically damaging internally than other types.

Rad (radiation absorbed dose): a basic unit of absorbed radiation dose. It is a measure of the amount of energy absorbed by the body. The rad is the traditional unit of absorbed dose. It is being replaced by the unit gray (Gy), which is equivalent to 100 rad. One rad equals the dose delivered to an object of 100 ergs of energy per gram of material.

Radiation: energy moving in the form of particles or waves. Familiar radiations are heat, light, radio waves, and microwaves. Ionizing radiation is a very high-energy form of electromagnetic radiation. Radiation sickness: See also acute radiation syndrome (ARS).

Radiation warning symbol: a symbol prescribed by the Code of Federal Regulations. It is a magenta or black trefoil on a yellow background. It must be displayed where certain quantities of radioactive materials are present or where certain doses of radiation could be received.

Radioactive contamination: the deposition of unwanted radioactive material on the surfaces of structures, areas, objects, or people. It can be airborne, external, or internal. See also contamination, decontamination.

Radioactive decay: the spontaneous disintegration of the nucleus of an atom.

Radioactive half-life: the time required for a quantity of a radioisotope to decay by half. For example, because the half-life of iodine-131 (I-131) is 8 days, a sample of I-131 that has 10 mCi of activity on January 1, will have 5 mCi of activity 8 days later, on January 9. See also: biological half-life, decay constant, effective half-life.

Radioactive material: material that contains unstable (radioactive) atoms that give off radiation as they decay.

Radioactivity: the process of spontaneous transformation of the nucleus, generally with the emission of alpha or beta particles often accompanied by gamma rays. This process is referred to as decay or disintegration of an atom.

Radioassay: a test to determine the amounts of radioactive materials through the detection of ionizing radiation. Radioassays will detect transuranic nuclides, uranium, fission and activation products, naturally occurring radioactive material, and medical isotopes.

Radiogenic: health effects caused by exposure to ionizing radiation.

Radiography: 1) medical: the use of radiant energy (such as x-rays and gamma rays) to image body systems. 2) industrial: the use of radioactive sources to photograph internal structures, such as turbine blades in jet engines. A sealed radiation source, usually iridium-192 (Ir-192) or cobalt-60 (Co-60), beams gamma rays at the object to be checked. Gamma rays passing through flaws in the metal or incomplete welds strike special photographic film (radiographic film) on the opposite side.

Radioisotope (radioactive isotope): isotopes of an element that have an unstable nucleus. Radioactive isotopes are commonly used in science, industry, and medicine. The nucleus eventually reaches a stable number of protons and neutrons through one or more radioactive decays. Approximately 3,700 natural and artificial radioisotopes have been identified.

Radiological or radiologic: related to radioactive materials or radiation. The radiological sciences focus on the measurement and effects of radiation.

Radiological dispersal device (RDD): a device that disperses radioactive material by conventional explosive or other mechanical means, such as a spray. See also dirty bomb.

Radionuclide: an unstable and therefore radioactive form of a nuclide.

Radium (Ra): a naturally occurring radioactive metal. Radium is a radionuclide formed by the decay of uranium (U) and thorium (Th) in the environment. It occurs at low levels in virtually all rock, soil, water, plants, and animals. Radon (Rn) is a decay product of radium.

Radon (Rn): a naturally occurring radioactive gas found in soils, rock, and water throughout the United States. Radon causes lung cancer and is a threat to health because it tends to collect in homes, sometimes to very high concentrations. As a result, radon is the largest source of exposure to people from naturally occurring radiation.

Relative risk: the ratio between the risk for disease in an irradiated population to the risk in an unexposed population. A relative risk of 1.1 indicates a 10% increase in cancer from radiation, compared with the "normal" incidence. See also risk, absolute risk.

Rem (roentgen equivalent, man): a unit of equivalent dose. Not all radiation has the same biological effect, even for the same amount of absorbed dose. Rem relates the absorbed dose in human tissue to the effective biological damage of the radiation. It is determined by multiplying the number of rads by the quality factor, a number reflecting the potential damage caused by the particular type of radiation. The rem is the traditional unit of equivalent dose, but it is being replaced by the sievert (Sv), which is equal to 100 rem.

Risk: the probability of injury, disease, or death under specific circumstances and time periods. Risk can be expressed as a value that ranges from 0% (no injury or harm will occur) to 100% (harm or injury will definitely occur). Risk can be influenced by several factors: personal behavior or lifestyle, environmental exposure to other material, or inborn or inherited characteristic known from scientific evidence to be associated with a health effect. Because many risk factors are not exactly measurable, risk estimates are uncertain. See also absolute risk, relative risk.

Risk assessment: an evaluation of the risk to human health or the environment by hazards. Risk assessments can look at either existing hazards or potential hazards.

Roentgen (R): a unit of exposure to x-rays or gamma rays. One roentgen is the amount of gamma or x-rays needed to produce ions carrying 1 electrostatic unit of electrical charge in 1 cubic centimeter of dry air under standard conditions. Sensitivity: ability of an analytical method to detect small concentrations of radioactive material.

Shielding: the material between a radiation source and a potentially exposed person that reduces exposure.

Sievert (Sv): a unit used to represent equivalent dose and effective dose. This relates the absorbed dose in human tissue to the effective biological damage of the radiation. Not all radiation has the same biological effect, even for the same amount of absorbed dose. Dose equivalent is often expressed as millionths of a sievert, or micro-sieverts (μSv). One sievert is equivalent to 100 rem.

S.I. units: the Systeme Internationale (or International System) of units and measurements. This system of units officially came into being in October 1960 and has been adopted by nearly all countries, although the amount of actual usage varies considerably.

Somatic effects: effects of radiation that are limited to the exposed person, as distinguished from genetic effects, which may also affect subsequent generations. See also teratogenic effects.

Stable nucleus: the nucleus of an atom in which the forces among its particles are balanced. See also unstable nucleus.

Stochastic effect: effect that occurs on a random basis independent of the size of dose. The effect typically has no threshold and is based on probabilities, with the chances of seeing the effect increasing with dose. If it occurs, the severity of a stochastic effect is independent of the dose received. Cancer is a stochastic effect. See also non-stochastic effect, deterministic effect.

Strontium (Sr): a silvery, soft metal that rapidly turns yellow in air. Sr-90 is one of the radioactive fission materials created within a nuclear reactor during its operation. Stronium-90 emits beta particles during radioactive decay.

Surface burst: a nuclear weapon explosion that is close enough to the ground for the radius of the fireball to vaporize surface material. Fallout from a surface burst contains very high levels of radioactivity. See also air burst.

Tailings: waste rock from mining operations that contains concentrations of mineral ore that are too low to make typical extraction methods economical.

Thermonuclear device: a “hydrogen bomb.” A device with explosive energy that comes from fusion of small nuclei, as well as fission.

Teratogenic effect: birth defects that are not passed on to future generations, caused by exposure to a toxin as a fetus. See also genetic effects, somatic effects.

Terrestrial radiation: radiation emitted by naturally occurring radioactive materials, such as uranium (U), thorium (Th), and radon (Rn) in the earth.

Thorium (Th): a naturally occurring radioactive metal found in small amounts in soil, rocks, water, plants, and animals. The most common isotopes of thorium are thorium-232 (Th-232), thorium-230 (Th-230), and thorium-238 (Th-238).

Transuranic: pertaining to elements with atomic numbers higher than uranium (92). For example, plutonium (Pu) and americium (Am) are transuranics.

Tritium: (chemical symbol H-3) a radioactive isotope of the element hydrogen (chemical symbol H). See also deuterium.

Unstable nucleus: a nucleus that contains an uneven number of protons and neutrons and seeks to reach equilibrium between them through radioactive decay (i.e., the nucleus of a radioactive atom). See also stable nucleus.

UNSCEAR: United Nations Scientific Committee on the Effects of Atomic Radiation.

Uranium (U): a naturally occurring radioactive element whose principal isotopes are uranium-238 (U-238) and uranium-235 (U-235). Natural uranium is a hard, silvery-white, shiny metallic ore that contains a minute amount of uranium-234 (U-234).

Uranium mill tailings: naturally radioactive residue from the processing of uranium ore. Although the milling process recovers about 95% of the uranium, the residues, or tailings, contain several isotopes of naturally occurring radioactive material, including uranium (U), thorium (Th), radium (Ra), polonium (Po), and radon (Rn).

Whole body count: the measure and analysis of the radiation being emitted from a person's entire body, detected by a counter external to the body.

Whole body exposure: an exposure of the body to radiation, in which the entire body, rather than an isolated part, is irradiated by an external source.

X-ray: electromagnetic radiation caused by deflection of electrons from their original paths, or inner orbital electrons that change their orbital levels around the atomic nucleus. X-rays, like gamma rays can travel long distances through air and most other materials. Like gamma rays, x-rays require more shielding to reduce their intensity than do beta or alpha particles. X-rays and gamma rays differ primarily in their origin: x-rays originate in the electronic shell; gamma rays originate in the nucleus. See also neutron.

APPENDIX C: REFERENCES

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