SYNOPSIS OF THE OAK RIDGE RADIATION PROTECTION RESEARCH NEEDS WORKSHOP

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ABSTRACT

Radiation protection is foundational to harnessing the societal benefits of radiation in nuclear energy, security, and medicine applications. Significant challenges in radiation protection remain unaddressed for challenges in the nuclear fuel cycle, nuclear medicine, emergency response, national defense, and space exploration remains unresolved, as the United States is lacking a coherent research strategy prioritizing radiation protection mission needs and gaps in scientific knowledge to meet these needs. Research and development in the field of radiation protection calls for cooperation among governmental agencies, emergency responders, research organizations, and the academic community. Amidst atrophying national expertise in radiation protection, the Radiation Protection Research Needs Workshop was spearheaded by the Oak Ridge Associated Universities, Oak Ridge National Laboratory, and the Health Physics Society. This workshop facilitated critical dialogue among radiation protection stakeholders in the governmental and scientific communities, including national laboratories, academic institutions, and industry partners. The workshop featured presentations representing 12 federal agencies and breakout sessions involving the identification of scientific drivers by subject matter experts in each of the following areas: new fuel cycles/reactors, dosimetry, medical physics, instrumentation and operations, decontamination and decommissioning, space radiation, national defense, emergency response, environmental modeling, and low-dose effects. The goal of this workshop was to stimulate the contributions by stakeholders in the development of a national strategic research agenda in the field of radiation protection. Consequently, the Health Physics Society has established a Special Task Force on Health Physics Research Needs, tasked with the prioritization of scientific drivers in radiation protection in the development of a national strategic research agenda.

KEYWORDS: research; radiation protection, national strategy, emergency response, defense, low dose, fuel cycle, medical physics, decommissioning, environmental, dosimetry, space; knowledge management; strategic planning; research agenda

INTRODUCTION

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. Radiation protection applications are inherent within the nuclear fuel cycle, nuclear medicine, emergency response, national defense, and space exploration. As such, challenges for ensuring the safe and secure use of ionizing radiation in society using the latest scientific approaches and technological tools continue to exist. Research and development in the field of radiation protection calls for cooperation among governmental agencies, emergency responders, research organizations, industry, and the academic community. 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 legacy roots in national and international 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 among radiation protection stakeholders in the federal government, state governments, and the scientific communities, including the Department of Energy (DOE) national laboratories and academic institutions.

The National Council on Radiation Protection and Measurements (NCRP) previously identified an impending critical crisis in human capital and announced an initiative to address this ritical need in NCRP Statement No. 12, “Where Are the Radiation Professionals (WARP)?” (NCRP 2015). This statement, commonly referred to as the WARP report, is based on a workshop of the same name, consisting of participation from 30 organizations from government, industry, academia, medicine, and professional societies. During the workshop, NCRP President John Boice explained that the goal of the WARP initiative was to kick off a “Manhattan Project” to replenish the dwindling supply of radiation professionals in the United States. In short, a national effort is needed to address this problem. From discussions at the workshop, 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 continues from health physics programs and from complementary fields (e.g., engineering, physical sciences, industrial hygiene, mathematics, social sciences).

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In an alternative approach, 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

In 1993, the NRCP published Report No. 117, "Research Needs for Radiation Protection." The report addresses research needs for establishing guidelines for protection from ionizing radiation. The full report elaborates 60 specific areas in which the contributors feel that additional research can make important contributions (NCRP, 1993). Information collected during development of the report was distilled down to five very specific central questions facing the radiation protection research community (Table 1).

Table 1. NRCP Report No. 117: Research Needs for Radiation Protection (NCRP 1993).

1. What are the overall risks associated with low-dose exposure?
2. How can we better define the spatial and temporal distribution of dose to improve the accuracy and precision of the dose term for dose response relationships at both macroscopic and microscopic levels?
3. To what extent do new advances in molecular genetics and structural biochemistry permit us to expand our knowledge of the effects of radiation, thereby shedding light on the steps leading to the production of cancer and other damage?
4. Given that we live in a world that has radiation in the environment, the work place, the clinic, and outer space, what preventive measures can we take to reduce exposure or the potential for exposure, and, when exposure has taken place, what intervening measures can be taken to minimize harm?
5. Given the complexity of radiation effects, what can we do to promote public understanding to ensure rational and informed judgements on policies related to the practice of radiation protection?

Twenty-five years later, the core tenets of the NCRP Report No. 117 study endure. 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 2).

Table 2. 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, research drivers must be identified 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.

The RPRN workshop format was divided into two core activities to ascertain the demand for radiation protection science counterbalanced with scientific challenges in radiation protection: (1) Technical sessions on research needs within the federal agencies presented by governmental representatives and (2) Breakout discussions on technical and scientific priorities by subject matter experts.

PLENARY

Background: Where are the Radiation Professionals

In June 2013, NCRP hosted a workshop to address a national crisis posed by the growing shortage of radiation professionals (NCRP 2015). At the RPRN Workshop, Richard Toohey, co-chair of the NCRP Council Committee 2 and invited plenary speaker, outlined the context of WARP in terms of human capital needs in the field of radiation protection. This question regarding the future supply of qualified radiation professionals has been raised by professional societies, the National Academy of Sciences, and the US Government Accountability Office as the baby boomers reach retirement age and transition out of the workforce. This issue has been considered independently by various entities, and the purpose of the RPRN workshop was to bring representatives of professional societies, government agencies, educational institutions, and the private sector together to exchange information and develop action plans to mitigate the dichotomy between the growing use of radiological methods in medicine, research, and industry and the declining numbers of available experts in radiological protection. The threat of radiological terrorism exacerbates the potential need for a cadre of highly trained radiation experts. NCRP Statement No. 12, "Where Are the Radiation Professionals?" (NCRP 2015) summarizes actions recommended by NCRP to ameliorate the situation.

A number of concrete recommendations emerged from the WARP Workshop in 2013 to help alleviate the projected shortage of radiation professionals, but all require funding to implement, and due to the nationwide and international aspects of this situation, the federal government must take the lead in preventing this impending crisis. Of relevance to this workshop is the recommendation that radiological sciences need to receive special emphasis in science, technology, engineering, and mathematics (STEM) education support efforts; university programs must be enlarged, and adequate support for both students and faculty research must be restored and increased.

Radiation Protection Research in Higher Education

Katherine Higley of Oregon State University commenced by reiterating the concerns from WARP regarding the alarming decline in the number of young professionals entering fields related to radiation protection. Other than a brief increase in enrollments in the 1990s, there has been a fairly consistent and ongoing decline in the number of health physics (HP) students since recordkeeping began in the 1970s (ORISE 2015). Although concern has been voiced numerous times about the shrinking and greying of the HP profession, there has not been a successful effort to alter the trend. Part of this is due to a reduced need as there has been a notable expansion of our understanding of radiation protection and control since the discovery of x-rays. As a profession, we have become more efficient at managing workplace safety, allowing us to streamline processes and eliminate redundancies. Federal research efforts into nuclear weapons production, and the safety concerns that accompany this work, have declined.

While industry has undergone several fundamental shifts to reduce expenses and enhance productivity, a related, but less visible change has been taking place in academia. State funding, in terms of the percentage of the costs for higher education, has been declining for several years, prompting colleges and universities to take a very hard look at where they spend their money. Academic programs that are small, thereby bringing in small amounts of tuition dollars, or those who do not pay their own way by winning research grant funding, are at great risk of being closed. Research expectations for tenured faculty are on the order of $500,000 to $1,000,000 per year at research universities. However, federal funding for academic research is becoming much more difficult to obtain. Without substantial research prospects, new HP faculty are not likely to receive tenure, and administrators are unlikely to rehire new faculty into the same discipline as existing HP faculty retire.

TECHNICAL SESSIONS ON RESEARCH NEEDS WITHIN THE FEDERAL AGENCIES

During the workshop, input was solicited from the 90 attendees, including representatives from industry, academia, nongovernmental organizations, and 12 federal agencies. The federal stakeholders outlined the mission of their agency/office, as well as the current and projected radiation protection needs to support required technologies to conduct mission efforts and scientific bases informing policy. Participants were asked to briefly introduce their organizations and to state why they were interested in radiation protection. A comprehensive series of questions were provided to align the discussion among federal agencies (Table 3).

Table 3. Radiation Protection Research Needs Presenter Questions

1. What research topics specific to your organization/expertise area, if critically addressed over the next several years, would significantly advance radiation protection?
    - What is the current state of practice/use in this field?
    - What are the institutional/knowledge needs?

2. Where are the gaps between established practices/knowledge and identified needs?
    - What is the ranking of each these needs as priorities given the importance of the need and the resources required to meet this priority?
    - Is there room for improvement/advancement/innovation within that system/technology?
    - Where are the areas of greatest uncertainty/risk?

3. How would you prioritize given the need of these advancements, and in consideration of the levels of risk/uncertainties to achieve these needs?
    - What are the research needs in this field in the next 3 to 5 years? How do we prioritize these needs in the broader long-term requirement?

Overview of Federal Research Needs

The Federal Research Needs Technical Session was initiated by Mike Boyd, as a representative of the Interagency Steering Organization on Radiation Standards (ISCORS), comprehensively discussed the historical needs within the federal government and industry and projected needs in radiation protection. In October 2002, the Institute for Alternative Futures, with support from the US Environmental Protection Agency (EPA), published *The Future of Radiation Protection: 2025—A Handbook for Improving Radiation Protection* (Olson 2002). To develop the report, 125 leaders in the field were asked to consider what would be the most significant radiation-related challenges that would need to be dealt with between now and 2025. The report provided insights into traditional mindsets that have to be adjusted to keep up with a changing landscape. A tacit assumption that the future will be much like the present has been largely replaced with the realization that the future is likely to be much different from the present if business continues as usual. An industry that has been based largely by a focus on the legacy issues of waste cleanup and management will shift to place greater importance on energy, national security, industrial and consumer protection, nuclear power plant decommissioning, and health applications. The mindset that radiological attacks and other terrorist acts are possible but need not be given high priority have already shifted to consider such attacks credible, making consideration of them a high priority. For survival, radiation protection as a community unto itself will need to focus on integration of radiation and environmental protection through shared principles for guiding action, combined databases, and risk harmonization. The research needs summarized in this report are still relevant today.

Within the federal agencies, research is needed and/or being conducted to improve the radiological protection of workers, the public, and the environment from radiation exposures arising from planned, existing, and emergency situations. Agencies need additional research to improve the monitoring for, detection of, and assessment of radioactivity in the environment. There is also a need for research to better understand the biological effects of

exposure to ionizing radiation, and the mechanisms leading to these biological effects and methods for mitigating the effects.

Environmental Protection Agency

Lowell Ralston elaborated how the EPA's roles and responsibilities in the nation's homeland security mission have evolved since the events of September 11, 2001. This expanded mission includes addressing terrorist attacks involving biological, chemical, or radiological agents by providing critical scientific research and capabilities to address homeland security threats. EPA has 10 divisions in 6 offices and 1 National Homeland Security Research Center whose roles and responsibilities involve radiation protection of people and the environment.

The research needs of the EPA are as diverse as its programmatic missions and include dosimetry, emergency response, environmental modeling, decontamination, radiation detection, and radiation operations. Specific needs from within each of the divisions can be consolidated within the following common themes:

- Development of nationally consistent procedures for sampling and analyses, decontamination, cleanup, and disposal
- Quality control/quality assurance
- Enhancement of laboratory capacity/capability
- Continued training and exercises
- Expanded public outreach and education
- Improvement of response tools and methods

Nuclear Regulatory Commission

Created by the Energy Reorganization Act of 1974, the Nuclear Regulatory Commission (NRC) is charged with licensing and regulating civilian use of nuclear energy to protect the public and the environment. Representing the NRC, Cynthia Jones emphasized that the NRC's focus is on issues of highest safety and regulatory significance and that the NRC is tasked with performing confirmatory and anticipatory research on new nuclear energy technologies. This research helps to maintain NRC's core capabilities while helping to cooperatively support the industry. Two of NRC's key research areas are (1) severe accidents and accident consequences and (2) radiation effects and environmental analysis. Under these two areas, the NRC is re-evaluating the dollar per person-rem value used in regulatory analysis and is developing technical bases for rulemaking associated with radiation protection.

The NRC's Radiation Protection Research Program and the Environmental Transport Research Program are conducted by the NRC's Office of Nuclear Regulatory Research (RES). These programs are agency-wide resources that provide technical support in the areas of radiation and environmental protection. The mission of the NRC's Radiation Protection Program is to assist the NRC in its goals of regulatory licensing, policy making, and

increasing public confidence. RES conducts research to support the NRC's evaluation and implementation of improvements to licensing, regulations, nuclear regulatory policy updates and changes and oversees studies toward publishing guidelines and publications for public consumption. The Environmental Transport Research Program provides improved technical bases and analytical tools for reviewing site characterization, monitoring, modeling, and remediation programs submitted by current and prospective licensees with regard to the release of radioactive materials to the environment from licensed nuclear facilities (NRC 2016).

Future drivers of NRC research will likely be a focus on stabilizing code development and maintenance, non-light water reactor (LWR) technologies, advanced-technology fuels and fuel cycles, and preservation of skills within the industry. More specific goals for research by or for the NRC include assessing health risks from low-dose/dose rates; improving realism in dose assessment; human reliability assessment; radiation considerations (e.g., dose coefficients, design/placement of filters) in the development of advanced reactors; transportation of radionuclides in aqueous media such as surface water and groundwater; establishment of lessons learned from domestic and international operating experience; and development of national baselines of health effects having a possible radiogenic origin, including thyroid effects, leukemia, and age-specific effects.

US Department of Energy

The Atomic Energy Act of 1957, Section 8(a), requires R&D activities relating to the protection of health during research and production activities. This requirement is fulfilled by conducting and supporting health studies to determine whether DOE workers and people living in communities near DOE sites are adversely affected by exposures to hazardous materials from DOE operations. Information gleaned from this effort is then used to protect and promote the health of DOE workers, their families, and residents of neighboring communities.

Isaf Al-Nabulsi of the DOE Office of Health and Safety (AU-10), within the Office of Environment, Health, Safety and Security (AU), outlined the mission focusing on establishing worker safety and health requirements and expectations for the DOE to ensure protection of workers from the hazards associated with DOE operations. This office is responsible for conducting and supporting domestic health studies to determine worker and public health effects from exposure to hazardous materials associated with DOE operations. AU-10 is also responsible for supporting low-dose health effects through the Japan Radiation Effects Research Foundation (RERF) and Russian health studies. RERF has been conducting studies of long-term health effects on atomic-bomb survivors since 1955, making it the longest surviving international cooperative research program. DOE and predecessor agencies have funded program for more than 70 years. The results of RERF research have become the world's most important guide for radiation-induced health effects, especially cancer, and are also used to develop standards for occupational exposures and to assess risks from medical exposure sources.

The Office of Science and the Office of Environment, Health, Safety and Security have both funded research on the health effects of low-dose radiation. The Office of Science established the Low Dose Radiation

Research Program in 1998 and funded it through fiscal year (FY) 2016. A primary focus of the program was radiobiological research, which examines molecular and cellular responses to radiation exposure. According to DOE's website for the program, the program provided data and information about the low-dose range of exposure, producing 737 peer-reviewed publications as of March 2012. The Office of Environment, Health, Safety and Security provided funding for epidemiological studies, including studies involving Japanese atomic bomb survivors (GAO 2017). The Low Dose Radiation Research Program was discussed in a separate session at this workshop.

National Cancer Institute

The National Cancer Institute (NCI) is one of 27 institutions under the National Institutes of Health. Within NCI, the Radiation Epidemiology Branch (REB) is situated in the Division of Cancer Epidemiology and Genetics. Choonsik Lee of the NCI-REB elaborated the REB's mission is to identify, understand, and quantify the risk of cancer in populations exposed to different types of radiation. Research is conducted to develop dosimetric, epidemiological, and statistical methods, while training future researchers in radiation and cancer epidemiology. Ongoing research includes long-term health effects in radiotherapy patients. To assess these effects, research is needed to improve dosimetry and risk models, to develop innovative dose measurement techniques for patients, and to evaluate and anticipate emerging radiotherapy techniques. NCI-REB is also evaluating the potential cancer risk from pediatric computed tomography (CT) scans and is planning to conduct a pooling analysis of CT risks for approximately one million children. These studies can be improved by establishing techniques to estimate risk from multiple exposures and by the incorporation of organ dose calculations into picture archiving and communication systems.

Research is also being conducted on the radiation-induced cancer incidence and mortality among radiologic technologists in the United States. Greater precision can be attained through the use of individualized dosimetry based on body size. NCI-REB is also in the process of evaluating thyroid doses to Chernobyl cleanup workers, childhood thyroid cancer incidence among children exposed to radiation as a result of the Chernobyl accident, and investigation of the heritability of radiation damage among parents that received preconception doses as a result of the Chernobyl accident.

US Food and Drug Administration

Stanley Stern elaborated how two centers and one office within the US Food and Drug Administration (FDA) have interests or missions related to radiation protection. The Center for Drug Evaluation and Research (CDER) reviews the development and marketing of safe and effective radiopharmaceuticals for diagnostic and therapeutic applications. CDER also reviews contrast agents used in medical imaging and medical countermeasures to acute radiation syndrome. The Center for Devices and Radiological Health (CDRH) reviews, clears, and approves marketing of any medical devices that emit radiation. The CDRH sets standards for any electronic product that emits radiation and sets the quality assurance standards for mammography under the Mammography Quality Standards Act and Program. Housed within the Office of the Commissioner, the Office of the Chief Scientist manages the

Office of Counterterrorism and Emerging Threats (OCET), which provides leadership, coordination, and oversight for FDA's national and global health security, counterterrorism, and emerging threats portfolios. This office serves as the focal point within the FDA for the US Department of Health and Human Services (HHS) Public Health Emergency Medical Countermeasures Enterprise and the US Department of Defense (DOD) medical countermeasure programs to support our nation's warfighters. OCET also coordinates FDA's Medical Countermeasures Initiative to facilitate the development of safe and effective medical countermeasures against chemical, biological, radiological, and nuclear agents and emerging threats, such as pandemic influenza.

The unified mission of these groups is to enhance drug safety and effectiveness, improve efficiency in development of radiopharmaceuticals, and develop medical countermeasures to radiation toxicity. Each facet of this mission requires research to understand the biodistribution of materials as well as the absorbed dose and associated effect on cancerous tissues and risk on healthy tissues. Research is needed to understand the variation between populations and the optimal method of administration. Continued research is essential to understanding the mechanisms for possible immunotoxicology and genotoxicology, adverse interactions with other medications, and the potential for contamination during pharmaceutical manufacturing. For the more than 85 approved diagnostic radiopharmaceuticals, the FDA emphasizes seeking an optimal balance between clinical benefit and radiological risk for patients and practitioners. Therapeutic applications likewise require a tradeoff between the lethality of the medication in targeted tissues and potential toxicity in healthy tissues.

European Approaches to Radiation Protection Research Programs

Werner Rühm provided insights on how the European Union organizes its radiation protection efforts under the CONCERT program and where US efforts may find common alignment. CONCERT comprises four radiation protection platforms, MELODI, ALLIANCE, NERIS, and EURADOS. The CONCERT-European Joint Programme for the Integration of Radiation Protection Research under Horizon 2020 operates as an umbrella structure for research initiatives jointly launched by the four platforms under CONCERT.

The Multidisciplinary European Low Dose Initiative (MELODI) is dedicated to radiation risk research at low doses. MELODI's research agenda is centered on the dose and dose-rate dependence of cancer risk, mechanisms behind non-cancer effects, and individual radiation sensitivities.

The European Radioecology Alliance (ALLIANCE) is tasked with bringing together R&D programs for the maintenance and enhancement of radioecological competencies and experimental infrastructures. ALLIANCE also seeks to address scientific and educational challenges in assessing the impact of radioactive materials on humans and the environment. This group focuses on three primary challenges: prediction of human and wildlife exposures by quantifying key processes influencing radionuclide transport, determination of ecological consequences of radioactive material exposure under realistic exposure conditions, and improvement of human and environmental protection by integrating radioecology into other risk assessment frameworks.

NERIS is the European Platform on Preparedness for Nuclear and Radiological Emergency Response and Recovery. This independent organization has a mission to establish a forum for dialogue and methodological development between all European organizations and associations taking part in decision making of protective actions in nuclear and radiological emergencies and recovery in Europe. NERIS focuses its research efforts on improving atmospheric and aquatic dispersion modeling, involvement and communication strategies for stakeholder and local preparedness, and improved dose assessments and decision support based on the most up-to-date radiation protection knowledge.

The European Radiation Dosimetry Group (EURADOS) is a network of more than 60 institutions and more than 500 scientists from the European Union, Switzerland, and Eastern and Central Europe. It serves the promotion of R&D and European cooperation in the field of the dosimetry of ionizing radiation. EURADOS research efforts include the fields of radiation protection, retrospective dosimetry, environmental radiation monitoring, radiobiology, radiation therapy, and diagnostic and interventional radiology. EURADOS has established a strategic research agenda with five separate visions. The first is an updated understanding of fundamental dose concepts and quantities. This leads to the second vision: improved radiation risk estimates for epidemiological cohorts. The first vision also ties directly into Vision 3: efficient dose assessment in case of radiological emergencies. The final two visions are integrated personalized dosimetry in medical applications and improved radiation protection of workers and the public.

The European Alliance for Medical Radiation Protection Research (EURAMED) is not technically under the CONCERT umbrella, but it shares some of the same goals and areas of research focus. Research under UEURAMED centers on measurement and quantification of ionizing radiation, tissue reactions and biological radiation risk, optimization of radiation exposure and harmonization of practices, justification of the medical uses of ionizing radiation, and development of an infrastructure for quality assurance.

CONCERT is a co-funded action that aims at attracting and pooling national research efforts with European efforts 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. The strategic research agendas developed under CONCERT are meant to be living documents that are periodically updated as issues are resolved and as new questions arise.

Radiation Protection Needs in National Security

The panel addressing radiation protection needs in national security addressed themes in defense and emergency response. Andrew Scott from US Department of Homeland Security, Craig Moss from ORNL, Dan Blumenthal from the National Nuclear Security Administration (NNSA), Adela Salame-Afie from the HHS Centers from Disease Control and Prevention (CDC), Brendan Palmer from the Federal Emergency Management Agency,

Jama Van Horne-Sealy from DOD(Army), and Luis Benevides from DOD (Navy) provided feedback on experiences and lessons learned at Fukushima as well as domestic emergency response exercises while assessing instrumentation needs and overarching challenges in data management (collection, analysis, and storage). Given that 5 years have passed since the incident at Fukushima-Daiichi, it was recommended that lessons learned must be examined to identify areas for improved technologies, standard operating procedures, and informed policy/decision making.

Equipment traditionally employed for occupational dosimetry monitoring was identified to have limited capabilities in emergency response capabilities. In emergency field operations, physical dosimetry equipment (personal dosimeters, field meters) is limited, and active dosimetry providing real-time data is required over passive dosimetry. Development of methodologies to conduct field bioassays to make on-site decisions regarding the operating environment was identified as an outstanding deficiency.

During field measurement activities, the desire to obtain accurate data in a timely manner while operating safely remains a critical objective. From ground measurements by responders in the field to remote methods such as large detectors on flying craft, integration of radiation detection spectrometry to identify the radionuclide and type of radiation contamination in the field remains paramount. In addition to innovation in instrumentation technologies, instrumentation calibration methods and appropriate education and training on field instrumentation are critical for effective data acquisition and decision making in the field.

Tools and methods are also required for decontamination. For example, in Fukushima, 30 ships and more than 200 aircraft were involved in the operation, which introduced issues with radioactive materials becoming concentrated in mechanical, hydrological, and filtration systems. Procedures and protocols had to be developed on site for the clearance of large, complex materials that were radiologically contaminated. Research on how to survey something the size of an aircraft carrier would have expedited the return of vehicles and equipment to US soil.

The discussion of radiation protection needs in national security concluded with a consensus on the need for standard operating procedures across domestic federal agencies and for authorities responsible for reporting to international counterparts. As emphasized earlier, operational standards remain critical for field instrumentation calibration and measurements, data collection, and management across all phases (early to late) and worker/public records, risk communication, and decontamination. Standards across quantities such as using the International System of Units become paramount in communications in international incidents. A large-scale event such as the Fukushima response generates large amounts of data that need to be processed and relayed to the decision makers. Resources for secure and timely collection, analysis/correlation, and management based on the myriad of field measurements and supporting information regarding operating conditions and hazard assessments need to be developed before the next mass mobilization event.

National Aeronautics and Space Administration

Eddie Semones from the National Aeronautics and Space Administration (NASA) discussed how space radiation is a major challenge to exploration for both near-Earth and interplanetary missions. Astronauts in spaceflight are exposed to a variety of radiation sources and types, including protons and heavy nuclei comprising galactic cosmic rays, with energy ranges from about 10 MeV to 10,000 MeV. Also of concern are the low- to medium-energy protons from solar particle events and the mixed field of neutrons and charged particles encountered on the surface of Mars. During training and qualification, astronauts endure a series of diagnostic tests and train through aircraft operations. Interplanetary crews will be exposed to a high linear energy transfer (LET) radiation environment composed of high-energy protons and high-atomic-number, high energy particles (HZEs) as well as secondary protons, neutrons, and fragments produced as a result of the interactions of these particles in shielding and tissue. Heavy ions are qualitatively different from x-rays or gamma-rays in that they are densely ionizing along the particle track; cause unique damage to biomolecules, cells, and tissues; and produce distinct patterns of DNA damage and distinct profiles of oxidative damage. Currently, no human data are available to estimate risk from the heavy ions encountered in space.

NASA has developed an approach to solve these problems, including the establishment of three NASA Specialized Centers of Research, a method for simulating space radiation at the NASA Space Radiation Laboratory, and funded research at more than 40 US universities. NASA is working with this established pool of high-quality external investigators to determine the radiation quality effects on biological damage, establish qualitative and quantitative differences between space radiation and x-rays or gamma rays, and understand the dependence of risk on the dose rates encountered in space. Studies are evaluating the biological mechanisms of cell/tissue repair and regulation, as well as the mechanisms determining individual radiation sensitivity. Studies are being conducted that evaluate the risk of both cardiovascular and central nervous system complications arising from exposure to HZE radiation during space travel. Methods to accurately predict the temporo-spatial variations in the space radiation environment are also being investigated to mitigate the risk of space exploration. Developing novel methods for shielding radiation that minimize the production of secondary radiation are continuously being evaluated while the fuel requirements for additional mass are being considered.

Electric Power Research Institute

The Electric Power Research Institute (EPRI) was formed in 1972 as a nonprofit organization dedicated to advancing the safe, reliable, affordable, and environmentally responsible electricity for society. EPRI takes each of these attributes seriously, looking to apply global collaboration, thought leadership, and science and technology innovation in the many aspects of electrical production and use. Donald Cool from EPRI emphasized how continuously evaluating several fundamental questions improves radiation protection through daily activities: Are recommendations, regulations, guidance, and operations informed by the best science and experience? Are we doing the right work, in the right way, at the right time? Where are opportunities to reduce the source? Can technology help us to further reduce exposures? Are all hazards addressed?

To reduce individual and collective exposures, EPRI is invested in the identification, qualification, and acceptance of technologies and approaches and the synthesis of current and future research into coherent explanations if dose effects. Working toward answering the fundamental questions, EPRI has established a set of base program research focus areas:

- "As low as reasonably achievable" strategies and technologies
- Source term reduction
- Radiation safety guidance
- Radiation measurements and dosimetry for workers and the public
- Effluent and radiological waste minimization
- Optimization of industrial and radiological safety
- Benchmarking and trending
- Low dose radiation health effects
- Decommissioning technology and strategies

RADIATION PROTECTION CHALLENGES AT LOW DOSES

In developing and applying radiation protection requirements and guidance for workers and the public—specifically, limits on dose or increased health risk and guidance levels on exposure—EPA, NRC, DOE, and FDA have generally taken the advice of scientific advisory bodies. In particular, they have relied on the advice of the International Commission on Radiological Protection, the National Council on Radiation Protection and Measurements, and the National Academies' Nuclear and Radiation Studies Board. This advice includes the use of the linear no-threshold model, which assumes that the risk of cancer increases with every incremental increase in radiation exposure. Advisory bodies have recognized challenges in accurately estimating cancer risks from very low doses of radiation exposure when using the linear no-threshold model. For example, much of the data on health effects of radiation exposure come from non-U.S. populations, such as Japanese atomic bomb survivors. These individuals received a large exposure to radiation over a short period of time (an acute exposure), and there is uncertainty about the extent to which the health effects for these populations can be extrapolated to a US population that is regularly (chronically) exposed to low-dose radiation (GAO 2017).

From FY 2012 through FY 2016, seven federal agencies obligated $209.6 million for research on the health effects of low-dose radiation, but they did not use a collaborative mechanism to address overall research priorities in this area. DOE and NIH accounted for most of the funding, with DOE obligating $116.3 million and NIH obligating $88.6 million, or about 56 percent and 42 percent of the total, respectively. The five other agencies—NRC, NASA, DOD, EPA, and CDC—obligated the remaining $4.7 million, or about 2 percent of the total (GAO 2017). Isaf al-Nabulsi elaborated how the Low Dose Radiation Research program within DOE Office of Science's Biological Systems Science Division started in 1998 to provide a critical scientific basis for setting radiation protection regulations by applying new techniques to measure biological changes at a very low-dose region (less than 100

mSv) to ultimately increase understanding of health outcomes from radiation exposures that are at or near current workplace exposure limits. The primary interest of this program is new mathematical/risk modeling projects that incorporate the latest low-dose and low-dose-rate biological research into mechanism-based models of tissue function.

Gaps in our knowledge of health effects in the low-dose region seriously impact our ability to make science-driven decisions after a large-scale radiological event with potentially major health and economic consequences. Protection of workers and the public from ionizing radiation exposure is currently based on the assumption that cancer incidence or mortality risk is a linear function of radiation dose. These assumptions are based on data from human health effects studies (Japanese atomic-bomb survivors, Russian health studies, workers, and occupational exposures). Most human health effects and model studies have dose-response relationships that provide data down to about 100 mSv, and there is a knowledge gap on the effects below that dose. DOE's low-dose radiation research program was intended to bridge this gap by increasing our fundamental understanding of how exposure to ionizing radiation affects human health.

In a September 2017 report, the United States Government Accountability Office recommended that the Secretary of Energy lead the development of a mechanism for interagency collaboration to determine roles and responsibilities for addressing priorities related to research on the health effects of low-dose radiation (GAO 2017). On December 18, 2017, H.R. 4675 was introduced by Roger Marshall (R-Kansas), calling for an amendment to the Energy Policy Act 2005 to provide for a low-dose radiation basic research program. The resolution calls for the Secretary of Energy to carry out research to "enhance the scientific understanding of, and reduce uncertainties associated with, the effects of exposure to low-dose radiation." The research is also intended to "inform improved risk-assessment and risk-management methods with respect to such radiation." Under the bill, the Energy Secretary would be required to submit a four-year research plan within 180 days of the bill being enacted, and the bill authorizes total spending of $100 million between FY 2018 and FY 2021. The bill was passed by the House of Representatives on February 13, 2018. To date, the senate has not voted on the measure.

Low dose discussion

John Boice from the NRCP and Michael Bellamy from ORNL moderated a group discussion on challenges in radiation studies at low doses. Risk estimates are based on extrapolation of data from high-dose, acute events. The discussion was initiated by a question on best practices integrating radiation biology with epidemiological data. From an epidemiological stance, the observable endpoint is cancer without consideration of the various biological processes that translate radiation-induced damage into cancer. Integration of radiation biology and epidemiology at low doses is further complicated by the dominance of confounding factors.

Biological processes are inherently integrated into observable cancer statistics. Some biological models have been incorporated into mechanistic risk estimates, such as those for breast cancer. However, there is an opportunity to investigate each of the mechanistic steps between a radiation exposure and the development of a

deterministic effect. As an example, there is a lack of available data on the rates of mutation and other processes that are intermediary between a dose and an observable effect.

Translation of findings of low-dose research into an implementable regulatory system was also discussed in the session. Traditionally, risk assessment and risk management have been treated as one. A risk assessment model should consider the distributions of individual radiation sensitivities and should reflect times-at-exposure and reflect our current biological understanding. Risk management takes these scientifically based assessments and weighs them against the risk associated with possible courses of action (for instance, evacuation after a large-scale event). There then exists a need to bridge the gap between scientific understanding and a regulatory approach to minimizing risk.

BREAKOUT DISCUSSIONS

On both days of the workshop, informal discussions were conducted in two breakout sessions. The first day's sessions focused on the following areas:

- Radiation protection issues with new fuel cycles and advanced reactor technologies
- Dosimetry
- Radiation protection in medical physics
- Instrumentation and operations

The second day's sessions focused on the following areas:

- Radiation protection needs in national defense
- Decontamination and decommissioning
- Radiation in space
- Environmental modeling
- Radiation protection needs in emergency response

Attendees maximized this opportunity to discuss developments in the advancement of radiation sciences. At the end of each day, chairs of each of the breakout sessions presented a short summary of the comments provided by the participants. Key themes from each of the breakout sessions are outlined in Table 4. The list is not exhaustive and is not intended to list specific projects or outcomes, but rather a general area of needed research.

Table 4. RPRN Breakout Session Research Priorities.

New Fuel Cycles/Reactors	Dosimetry/Risk	Medical Physics	Instrumentation and Operations	Decontamination and Decommissioning
Chairs: Cynthia Jones (NRC), Bojan Petrovic (Georgia Tech)	*Chairs: Wes Bolch (UFL), Shaheen Dewji (ORNL)*	*Chairs: Wayne Newhauser (LSU), Niek Schreuder*	*Chairs: Mike Stafford (ORNL), Frazier Bronson (Mirion)*	*Chairs: Wendy Cain (DOE), John Cardarelli (EPA)*

		(Provision)		
• Comparison of dose impact to existing cycles • Modeling and planning for radiological emergencies • Waste handling and disposal • Variation in environmental pathways • Incorporation of new shielding technologies into reactor design	• Improvement of radiation risk estimates from biological data • Determination of cancer risk due to exposures at low dose • Personalization of dosimetry in medical applications • Rapid and accurate dose assessment during radiological emergencies • Refinement of the use of theoretical dose concepts and quantities • Enhancement of radiation measurement systems • Development of environmental dosimetry for non-human biota	• Improve methods for calculating dose and corresponding risk of radiogenic cancer • Develop methods for personalized radiation dose and risk calculations suitable for clinical applications • Improve methods for calculating dose and corresponding non-cancer late effects • Improve simulation methods to model advanced, emerging, and next-generation radiation therapy and imaging technologies	• Improved neutron instrumentation • Indoor position logging • Improved field-appropriate spectroscopy • Combination (radiological and chemical) detectors • Direction-specific detectors • Improvement to instrument ruggedness • Instrumentation that can detect alpha, beta, neutron, and gamma radiation • Development of instruments that are hardened against radiation damage • Definition and pathway for very low-level waste	• Development of risk-based cleanup levels using ecological system transport • Characterization of radon for in situ mines • Improved characterization technologies for sub-surface soils and groundwater • Novel decontamination techniques • Development of remote-handling techniques • Determination of confounding effects of radiological and chemical exposures • Waste volume reduction • Determination of volumetric contamination • Waste disposal

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Space Radiation	National Defense	Emergency Response	Environmental Modeling
Chairs: Eddie Semones (NASA), Wouter de Wet (UTK)	*Chairs: Luis Benevides (DOD-Navy), Jama VanHorne-Sealy (DOD-Army)*	*Chairs: John Crapo (NNSA), Adela Salame-Alfie (CDC)*	*Chairs: Nicole Martinez (Clemson), Jerry Hiatt (NEI)*
• Optimization of shielding thickness • Secondary radiation produced in shielding • Cross sections for heavy, energetic particle interactions • Comparative dose response studies • Individual, genetic-based risk profiles • Central nervous system damage effects • Radiogenic cardiovascular effects • Low-dose-rate effects from all (incl. heavy) ions • Improved astrophysical models to minimize dose based on mission timing • On-site construction of shielding	• Determination of protection factors for vehicles and structures • Improved radiation transport codes that allow incorporation of CAD data • Biodosimetry for rapid triage • Dosimetry models for combat animals • Personnel performance degradation from medical countermeasures • Development of coatings that inhibit contamination due to fallout • Portable, rugged detection instrumentation • Unmanned detection robots • Urban plume modeling • Hardening of electronics against radiation damage	• Atmospheric dispersion modeling • Contaminant migration modeling • Population dose estimation • Dose assignment for emergency response workers • Biodosimetry for rapid triage • Improved bioassay for alpha emitters • Assay for low-energy contaminants • Post-event decontamination • Urban environment activation • Directional radiation detectors	• Radionuclide fate and transport modeling • Incorporation of sport hunting and wild plant foraging in pathway models • Identification of indicator species within each climatological area • Confounding effects due to chemical and physical stressors in conjunction with radiological exposures • Determination of biological effects risk due to exposures at low dose

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CONCLUSIONS

With expansion of the use of radioactive materials and radiation-generating devices, as well of the radiation exposure potential inherent in extended space travel, demands on the health physics community are increasing at a rapid rate. This comes at the very time when many of the seasoned health physicists are retiring from the profession. Changing technologies and improved understanding of the biological effects of radiation exposure are driving the need for a whole new generation of radiation-monitoring instrumentation, personnel dosimetry, and dosimetric models that are more sensitive and better able to take into account responses to differing energy levels of radiation. Among the suggested actions that NCRP recommended to prevent this impending problem were the restoration of significant federal and state funding for scholarships, fellowships, faculty research, and national laboratories.

The RPRN workshop was structured so that federal agency research needs could be identified, as these agencies are the primary funders of radiation protection work. Mission-specific requirements for the federal agencies were identified in the context of the technical presentations from each representative, where scientific drivers were explored in the afternoon breakout sessions. The workshop was successful in identifying a critical gap in radiation protection research. There are resources and shared needs among the federal agencies, many of which overlap with proposed scientific innovation; however, a nebulous area between the federal missions and basic science innovation was identified. The development of mission-ready technologies typically spans many years and follows a series of steps toward implementation. Therefore, a dedicated program is recommended that would fund mission-specific work with higher levels of technological readiness, basic science in radiation protection, and the intermediate steps between benchtop proof of concept and commercial readiness.

PATH FORWARD

Identifying research needs and communicating those needs to agency and congressional stakeholders is of critical importance to the protection of radiation workers and the public and to the health physics profession. Research funding is a necessary condition for ongoing viability of academic programs in radiation protection and national laboratory research institutions, preservation of radiation protection expertise, and the maintenance of a pipeline of adequately trained radiation protection professionals. The goal of this effort was to stimulate the contribution of stakeholders to the development of a national strategic research agenda in the field of radiation protection. This research agenda will be multidisciplinary in science, tailored to societal needs, make full use of newly gained knowledge in all disciplines of life sciences and humanities and to fully integrate education and training, especially of the young, to build the competences needed for a successful and sustainable radiation protection discipline today and in future.

To capitalize on the discussions within this workshop, the HPS has established a Special Task Force on Health Physics Research Needs. The task force has been directed to 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 and national laboratory research institutions. The task force will make recommendations to the HPS Executive Committee on a path forward for supporting and advancing research needs in radiation protection. Specific areas the Task Force will address include the following:

- Identification of scientific drivers supporting the national needs in radiation protection research
- Review of the Strategic Research Agenda developed from the outputs of the RPRN Workshop and determination of how it can be a living document that reflects the radiation protection research areas critical to the completion of the nation's missions.
- Assessment of ongoing status of radiation protection research funding and needs in the United States, including research supported by federal, state and private sector funds
- Supporting communication of research needs to appropriate stakeholders, including congressional appropriators on Capitol Hill
- Prioritization of challenges will be based on scientific merit, national relevance, impact on mission planning and completion, feasibility within given resource constraints, time sensitivity, and potential impact on complementary disciplines.

Each of the identified scientific challenges, with their associated research lines, will be developed as a separate section of a Strategic Research Agenda. Each will include a vision statement of what should be accomplished over the next 5, 10, and 20 years in that area of radiation protection. The development of a strategic research agenda involving all stakeholders will ensure that this living document will continue to reflect the radiation protection research areas critical to the completion of the nation's needs.

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Figure 1. Radiation Protection Research Needs Workshop participants, held June 5-6, 2017, in Oak Ridge, Tennessee. Chairs: Nolan Hertel (Georgia Tech/ORNL), Eric Abelquist (ORAU); Technical Program Organizers: Shaheen Dewji (ORNL), Jason Davis (ORAU).