The Future of Advanced Nuclear Technologies: Interdisciplinary Research Team Summaries

DETAILS

128 pages | 6 x 9 | PAPERBACK
ISBN 978-0-309-30086-5 | DOI 10.17226/18705

AUTHORS

The National Academies Keck Futures Initiative

THE NATIONAL ACADEMIES
KECK FUTURES INITIATIVE

THE FUTURE OF ADVANCED NUCLEAR TECHNOLOGIES

INTERDISCIPLINARY RESEARCH TEAM SUMMARIES

Conference
Arnold and Mabel Beckman Center
Irvine, California
November 15-17, 2013

THE NATIONAL ACADEMIES PRESS
Washington, D.C.
www.nap.edu

THE NATIONAL ACADEMIES PRESS 500 Fifth Street, NW Washington, DC 20001

NOTICE: The Interdisciplinary Research (IDR) team summaries in this publication are based on IDR team discussions during the National Academies Keck *Futures Initiative* Conference on The Future of Advanced Nuclear Technologies held at the Arnold and Mabel Beckman Center in Irvine, California, November 15-17, 2013. The discussions in these groups were summarized by the authors and reviewed by the members of each IDR team. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the IDR teams and do not necessarily reflect the view of the organizations or agencies that provided support for this project. For more information on the National Academies Keck *Futures Initiative* visit www.keckfutures.org.

Funding for the activity that led to this publication was provided by the W. M. Keck Foundation. Based in Los Angeles, the W. M. Keck Foundation was established in 1954 by the late W. M. Keck, founder of the Superior Oil Company. In recent years, the Foundation has focused on Science and Engineering Research; Medical Research; Undergraduate Education; and Southern California. Each grant program invests in people and programs that are making a difference in the quality of life, now and for the future. For more information visit www.wmkeck.org.

International Standard Book Number-13: 978-0-309-30086-5
International Standard Book Number 10: 0-309-30086-X

Additional copies of this report are available from the National Academies Press, 500 Fifth Street, NW, Keck 360, Washington, DC 20001; (800) 624-6242 or (202) 334-3313; http://www.nap.edu.

Printed in the United States of America

THE NATIONAL ACADEMIES

Advisers to the Nation on Science, Engineering, and Medicine

The **National Academy of Sciences** is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. Upon the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Ralph J. Cicerone is president of the National Academy of Sciences.

The **National Academy of Engineering** was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. C. D. Mote, Jr., is president of the National Academy of Engineering.

The **Institute of Medicine** was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, upon its own initiative, to identify issues of medical care, research, and education. Dr. Harvey V. Fineberg is president of the Institute of Medicine.

The **National Research Council** was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Ralph J. Cicerone and Dr. C. D. Mote, Jr., are chair and vice chair, respectively, of the National Research Council.

www.national-academies.org

Copyright National Academy of Sciences. All rights reserved.

THE NATIONAL ACADEMIES KECK *FUTURES INITIATIVE* THE FUTURE OF ADVANCED NUCLEAR TECHNOLOGIES STEERING COMMITTEE

RICHARD A. MESERVE, Chair (NAE), President, Carnegie Institution for Science
S. JAMES ADELSTEIN (IOM), Paul C. Cabot Distinguished Professor of Medical Biophysics, Harvard Medical School
JOHN S. APPLEGATE, Executive Vice President for University Regional Affairs, Planning, and Policy, Walter W. Foskett Professor of Law, Indiana University
ALBERT CARNESALE (NAE), Chancellor Emeritus and Professor, University of California, Los Angeles
THOMAS B. COCHRAN, Consulting Senior Scientist and former Director of the Nuclear Program, Natural Resources Defense Council, Inc. (NRDC)
MICHAEL L. CORRADINI (NAE), Professor, Department of Engineering Physics, University of Wisconsin–Madison
ROBERT C. DYNES (NAS), President Emeritus, Professor, Department of Physics, University of California, San Diego
CHRISTOPHER B. FIELD (NAS), Director, Department of Global Ecology, Carnegie Institution for Science
Hedvig Hricak (IOM), Chair, Department of Radiology, Memorial Sloan-Kettering Cancer Center
THOMAS H. ISAACS, E.O. Lawrence Livermore National Laboratory
FRED A. METTLER, Professor Emeritus, Department of Radiology, New Mexico Federal Regional Medical Center, The University of New Mexico
WARREN MILLER, JR. (NAE), TEES Distinguished Research Professor, Texas A&M University System
PHILIP R. SHARP, President, Resources for the Future

Staff

KENNETH R. FULTON, Executive Director
KIMBERLY A. SUDA-BLAKE, Senior Program Director
ANNE HEBERGER MARINO, Program Officer
CRISTEN KELLY, Associate Program Officer
RACHEL LESINSKI, Program Associate

Consultant

BARBARA J. CULLITON, Director, NAKFI Science Writing Scholar Program

The National Academies
Keck *Futures Initiative*

THE NATIONAL ACADEMIES KECK *FUTURES INITIATIVE*

The National Academies Keck *Futures Initiative* was launched in 2003 to stimulate new modes of scientific inquiry and break down the conceptual and institutional barriers to interdisciplinary research. The National Academies and the W. M. Keck Foundation believe that considerable scientific progress will be achieved by providing a counterbalance to the tendency to isolate research within academic fields. The *Futures Initiative* is designed to enable scientists from different disciplines to focus on new questions, upon which they can base entirely new research, and to encourage and reward outstanding communication between scientists as well as between the scientific enterprise and the public.

The *Futures Initiative* includes three main components:

Futures Conferences

The *Futures* Conferences bring together some of the nation's best and brightest researchers from academic, industrial, and government laboratories to explore and discover interdisciplinary connections in important areas of cutting-edge research. Each year, some 150 outstanding researchers are invited to discuss ideas related to a single cross-disciplinary theme. Participants gain not only a wider perspective but also, in many instances, new insights and techniques that might be applied in their own work. Additional pre- or post-conference meetings build on each theme to foster further communication of ideas.

Selection of each year's theme is based on assessments of where the intersection of science, engineering, and medical research has the greatest potential to spark discovery. The first conference explored *Signals, Decisions, and Meaning in Biology, Chemistry, Physics, and Engineering.* The 2004 conference focused on *Designing Nanostructures at the Interface between Biomedical and Physical Systems.* The theme of the 2005 conference was *The Genomic Revolution: Implications for Treatment and Control of Infectious Disease.* In 2006 the conference focused on *Smart Prosthetics: Exploring Assistive Devices for the Body and Mind.* In 2007 the conference explored *The Future of Human Healthspan: Demography, Evolution, Medicine, and Bioengineering.* In 2008 the conference focused on *Complex Systems.* The 2009 conference explored *Synthetic Biology: Building on Nature's Inspiration.* The 2010 conference focused on *Seeing the Future with Imaging Science.* The 2011 conference focused on *Ecosystem Services.* The 2012 conference focused on *The Informed Brain in a Digital World* and the 2013 conference explored *The Future of Advanced Nuclear Technologies.* The 2014 conference will explore collective behavior from cells to societies.

Futures Grants

The *Futures* Grants provide seed funding to *Futures* Conference participants, on a competitive basis, to enable them to pursue important new ideas and connections stimulated by the conferences. These grants fill a critical missing link between bold new ideas and major federal funding programs, which do not currently offer seed grants in new areas that are considered risky or exotic. These grants enable researchers to start developing a line of inquiry by supporting the recruitment of students and postdoctoral fellows, the purchase of equipment, and the acquisition of preliminary data—which in turn can position the researchers to compete for larger awards from other public and private sources.

NAKFI Communications

The Communication Awards are designed to recognize, promote, and encourage effective communication of science, engineering, medicine, and/or interdisciplinary work within and beyond the scientific community. Each year the *Futures Initiative* awards $20,000 in prizes to those who have advanced the public's understanding and appreciation of science, engineering, and/or medicine. The awards are given in four categories:

books, film/radio/TV, magazine/newspaper, and online. The winners are honored during a ceremony in the fall in Washington, DC.

NAKFI cultivates science writers of the future by inviting graduate students from science writing programs across the country to attend the conference and develop interdisciplinary research (IDR) team discussion summaries and a conference overview for publication in this book. Students are selected by the department director or designee, and prepare for the conference by reviewing the webcast tutorials and suggested reading, and selecting an IDR team in which they would like to participate. Students then work with NAKFI's science writing student mentor to finalize their reports following the conferences.

Facilitating Interdisciplinary Research Study

During the first 18 months of the Keck *Futures Initiative*, the Academies undertook a study on facilitating interdisciplinary research. The study examined the current scope of interdisciplinary efforts and provided recommendations as to how such research can be facilitated by funding organizations and academic institutions. *Facilitating Interdisciplinary Research* (2005) is available from the National Academies Press (www.nap.edu) in print and free PDF versions.

About the National Academies

The National Academies comprise the National Academy of Sciences, the National Academy of Engineering, the Institute of Medicine, and the National Research Council, which perform an unparalleled public service by bringing together experts in all areas of science and technology, who serve as volunteers to address critical national issues and offer unbiased advice to the federal government and the public. For more information, visit www.nationalacademies.org.

About the W. M. Keck Foundation

Based in Los Angeles, the W. M. Keck Foundation was established in 1954 by the late W. M. Keck, founder of the Superior Oil Company. The Foundation's grant making is focused primarily on pioneering efforts in the areas of Science and Engineering Research; Medical Research; Undergraduate Education; and Southern California. Each grant program invests in people and programs that are making a difference in the quality of life, now and in the future. For more information, visit www.wmkeck.org.

National Academies Keck *Futures Initiative*
100 Academy, 2nd Floor
Irvine, CA 92617
949-721-2270 (Phone)
949-721-2216 (Fax)
www.keckfutures.org

Preface

At the National Academies Keck *Futures Initiative* Conference on The Future of Advanced Nuclear Technologies, participants were divided into 14 interdisciplinary research (IDR) teams. The teams spent 9 hours over 2 days exploring diverse challenges at the interface of science, engineering, and medicine. The composition of the teams was intentionally diverse, to encourage the generation of new approaches by combining a range of different types of contributions. The teams included researchers from science, engineering, and medicine, as well as representatives from private and public funding agencies, universities, businesses, journals, and the science media. Researchers represented a wide range of experience—from postdocs to those well established in their careers—from a variety of disciplines that included science and engineering, medicine, physics, biology, economics, and behavioral science.

The teams needed to address the challenge of communicating and working together from a diversity of expertise and perspectives as they attempted to solve a complicated, interdisciplinary problem in a relatively short time. Each team decided on its own structure and approach to tackle the problem. Some teams decided to refine or redefine their problems based on their experience.

Each team presented two brief reports to all participants: (1) an interim report on Saturday to debrief on how things were going, along with any special requests; and (2) a final briefing on Sunday, when each team:

- Provided a concise statement of the problem;
- Outlined a structure for its solution;
- Identified the most important gaps in science and technology and recommended research areas needed to attack the problem; and
- Indicated the benefits to society if the problem could be solved.

Each IDR team included a graduate student in a university science writing program. On the basis of the team interaction and the final briefings, the students wrote the following summaries, which were reviewed by the team members. These summaries describe the problem and outline the approach taken, including what research needs to be done to understand the fundamental science behind the challenge, the proposed plan for engineering the application, the reasoning that went into it, and the benefits to society of the problem solution. Because of the popularity of some topics, two or three teams were assigned to explore the subjects.

Eight tutorials were launched throughout the summer to help bridge the gaps in terminology used by the various disciplines. Participants were encouraged to listen to all of the tutorials prior to the November conference.

Contents

IDR TEAM SUMMARIES

APPENDIXES

To listen to the podcasts or view the conference presentations, please visit our website at www.keckfutures.org.

Conference Summary

Chris Palmer, Freelance Science Writer

Since its inception, the nuclear enterprise has played two extreme roles: as a limitless source of clean energy, promising to replace fossil fuels, and as the harbinger of doom, raising the specter of nuclear annihilation and environmental disasters such as Chernobyl. As fears have swelled, the development of technology using nuclear power has stalled, with little progress in the past decades. And while some countries—Russia, China, and India—are accelerating their nuclear power programs, every time there is a nuclear accident, some other countries—the United States and, more recently, Germany—scale back research and development. In the United States, 104 nuclear reactors were constructed between 1965 and 1977, but ground has been broken on only three reactors since then. In 2011, just days after the Fukushima Daiichi nuclear disaster in Japan, the German government declared it would close all of the country's nuclear plants by 2022.

Beyond the public's apprehension concerning the safety of nuclear power, which calls out for better communications strategies, several challenges lie ahead for the nuclear enterprise in the United States. The workforce in nuclear technology is aging, there is an overreliance on large, high-risk reactor designs, and the supply of radioisotopes for nuclear medicine remains unstable—all problems crying out for solutions.

The National Academies Keck Futures Initiative (NAKFI) Conference in 2013 focused on the Future of Advanced Nuclear Technologies to generate new ideas about how to move nuclear technology forward while making the world safer and more secure. Ernest Moniz, U.S. Secretary of the

Department of Energy, spoke about the need to maximize both safety and energy production in his keynote address. Paraphrasing President Obama's position on nuclear energy, which plays a strong role in the administration's "all of the above" energy strategy, Moniz said, "When we enhance nuclear security we're in a stronger position to harness safe, clean nuclear energy and when we develop new, safer approaches to nuclear technology, we reduce risk of nuclear proliferation and terrorism."

Conference participants joined one of 14 Interdisciplinary Research (IDR) teams each comprising about half a dozen leading researchers and thinkers—including engineers, material scientists, policy makers, social scientists, and writers—to collaborate on creative solutions to challenges designed to propel the policy, engineering, and social aspects of the nuclear enterprise forward.

PROMOTING U.S. NUCLEAR INFLUENCE

Since the dawn of the nuclear age, the United States has dominated the global nuclear enterprise. The United States has built and now maintains an unparalleled research and development program within federal and university laboratories. The nation's regulatory system is still considered the global gold standard, and the United States remains firmly committed to safety, security, nonproliferation, waste management, and protection of the environment. However, U.S. influence has slowly eroded as Russia, China, India, and South Korea have each developed significant nuclear programs that account for the majority of new plants under construction. Among these four nations, 70 plants exist and another 69 are being built. Meanwhile, the United States has not completed construction on a new reactor in more than 30 years and its aging workforce of highly trained nuclear engineers is set to retire. IDR Team 5 considered the means by which the United States can reassert its interests and influence in the global nuclear market.

The team focused primarily on economic solutions—collectively referred to as Nuclear 2.0—to prop up U.S. nuclear interests. They imagined expanding export markets for nuclear reactors, encouraging entrepreneurship and startup funding for small modular reactors, developing new revenue streams for nuclear power such as water desalination and waste heat processing, and enticing oil and gas companies to invest in nuclear power. Nuclear 2.0 would also include provisions for propagating the U.S. regulatory procedures for safety and waste management as well as its strategies for emergency management and cleanup following nuclear accidents.

NUCLEAR POWER IN A NUCLEAR WEAPON-FREE WORLD

Over a century of fossil fuel use has polluted our water and air, accelerated the warming of the planet, and spurred regional conflicts. Nuclear technology offers a viable option for providing an efficient, renewable, and clean source of energy. However, current nuclear technology relies heavily on the production of low-enriched uranium, which can be used to create weapons-grade, highly enriched uranium. With more and more countries working to ramp up their own nuclear energy programs, concerns arise that burgeoning nuclear technology in those countries may be subverted for the creation of weapons. Participants in IDR Challenge 6 considered ways to make civilian nuclear power more compatible with zero (or with a smaller number of) nuclear weapons. Discussions focused on technical, economic, and policy solutions.

On the technical front, challenge participants suggested a move toward powering reactors with thorium fuels, which cannot be used to make weapons-grade plutonium. They also explored alternatives to light water reactors, such as fuel-once reactors that do not use reprocessed fuel and small modular reactors, in order to reduce the amount of nuclear waste maintained on-site as a byproduct of energy production.

On the economic front, team members imagined the creation of a competitive international market for nuclear fuel to eliminate countries' economic incentive to develop their own nuclear programs. A limited number of global companies could enter into full service agreements with countries wanting to participate in the nuclear enterprise to provide reactor installation, cheap fuel, waste disposal, maintenance, and, more important, the take back of spent fuel. Each supplier would be held to similar standards and each buyer country would be supplied with the same standardized, tamper-resistant technologies to keep all countries on a level playing field. Such equal-partner relationships would create a sense of shared responsibility for safety and security for all members. As an added layer of transparency, global fuel cycle resources could be monitored with an open access database, ensuring that no resources were diverted into weapons programs.

SAFEGUARDING SPECIAL NUCLEAR MATERIALS

A critical facet of the nuclear enterprise is safeguarding the special nuclear materials (SNMs)—plutonium, uranium-233, or uranium enriched in the isotopes of uranium-233 or uranium-235—that are formed in nuclear reactors or extracted from spent nuclear fuel. Whereas the vast majority—up to 99 percent—of SNMs are secured in known locations, the whereabouts of about 1 percent of SNMs are currently unknown. To prevent the illicit use of SNMs, members of IDR Team 3 thought about approaches to both keep close track of the secured 99 percent and detect the missing 1 percent. SNMs can be modified so they are more easily detected if stolen or misplaced. Team members suggested embedding SNMs in packaging that emits a GPS-linked alarm if tampered with or moved. The materials themselves can also be modified to produce an active chemical, electrical, or thermal signal for easy tracking in case of loss or theft.

Radiation detectors are currently capable of locating unsecured, highly shielded SNMs, but only if they are bundled in large quantities and only at limited locations such as border checkpoints. Improvements in detection technology are needed for smaller amounts, as are methods for deploying that technology more broadly. Technological innovations can come in the form of detecting signatures of material used for radiation shielding and developing novel sensor architecture such as neutron-interception semiconducting chips. In general, sensors need to be cheaper, smaller, and mobile in order to create a widely distributed detection network supported by public and private partners. In addition, novel computational methods are needed to make sense of the network's data.

LIGHT WATER REACTORS

The vast majority of nuclear power generated in the world today comes from light-water reactors (LWRs) in which fuel, packed into a protective cladding, heats water to produce steam that drives giant turbines. The harsh conditions inside reactors can cause both fuel and cladding to crack, erode, and break into small pieces. IDR Team 2 centered on developing a novel type of fuel for these reactors to maximize performance and safety, while enhancing waste disposal options and reducing the cost of disposing spent fuel.

Since the safety of fuel for LWRs is closely tied to the cladding in which it is placed, the teams focused on improvements to the fuel-cladding complex. IDR Team 2B envisioned fuel pellets in a donut-shaped casing with inner and outer cladding. Water would run across the outside surface, as well as though a central hole, thereby transferring heat more quickly and increasing energy efficiency. Honeycomb fuel designs were also discussed.

The team also called for greater access to computational and experimental facilities for nuclear engineers to optimize fuel-cladding designs.

IDR Team 2A imagined an annular or ring-shaped design with coolant flowing through internal channels that could be protected by rupture disks in the case of tube failure. The team also called for modifying reactor designs to run at lower power to ensure safety requirements could more easily be met while reducing the amount of nuclear material that enters the fuel cycle.

RADIONUCLIDES AND RADIOPHARMACEUTICALS

Participants tackling IDR Challenge 1 were asked to identify improvements in technology to ensure the future development and supply of radionuclides and radiopharmaceuticals.

The United States is by far the leading consumer of radioisotopes for diagnostic imaging, the most widely used being technetium-99m (Tc-99m). Yet, there are no Tc-99m production plants in the United States, making the country vulnerable to periodic interruptions in overseas production. Therefore, reflecting one of the directives of the American Medical Isotope Production Act of 2012, one of the primary aspects of this challenge was to find a way to maintain a reliable supply of Tc-99m. However, Tc-99m's precursor, molybdenum-99 (Mo-99), is made from highly enriched uranium, raising nonproliferation concerns. These concerns drove the two IDR-1 teams to focus on the development of alternative radionuclides and radiopharmaceuticals.

One bottleneck in the development of novel radioisotopes is the regulatory process, which holds radionuclides to the same testing standards as conventional disease therapies, even though radionuclides are given at vastly smaller doses, often just once or a small handful of times in the course of care. Each of the three teams suggested that relaxing regulations and streamlining the approval process could dramatically speed up the time to market. Reflecting the conference's broad emphasis on transparency and sharing, Team 1B proposed incentives for researchers to submit data about new imaging agents to a public toxicology and pharmacokinetics database so that other researchers would not have to repeat safety studies of compounds that have already been tested. Team 1B also emphasized increased collaboration with clinicians to determine their imaging needs. Most of the more than 350 cyclotrons around the world produce just a single type of radionuclide. To accelerate the adoption of a diversity of new radionuclides, Team 1A recommended designing the devices so that they can manufacture a variety of radionuclides. The team also suggested that the use of new radionuclides could be promoted by the creation of service providers that handle all of a client's needs—from radioisotope creation to separation and preparation for point-of-care applications.

NOVEL APPLICATIONS

The two decades following the dawn of the nuclear age saw an explosion in creative ways to harness the power of the atom. However, development of nuclear technologies has stagnated since the 1960s as fears about nuclear power and proliferation permeated society. The two IDR-7 teams were asked to recall this early creative period and identify novel applications of nuclear phenomena that could benefit humankind.

IDR Team 7A focused on the energy-producing potential of nuclear phenomena. They imagined a combined heat and power plant in which radioactive particles interact with semiconductor chips to create electricity, akin to the process that takes place in solar panels. This application could be built into a solid-state generator with no moving parts, making it ideal for use in developing nations lacking the resources to maintain and repair more complex reactor designs. The team also pointed to new research confirming the ability to produce hydrogen in high-temperature (200 degrees Celsius) reactors that could dramatically reduce the cost of fuel cells for vehicles.

Increasing the world's access to food drove the discussions of IDR Team 7B. The team proposed irradiating nonpotable water to make it safe enough to irrigate crops, thereby reducing the need to use fresh drinking water to grow food. The team also suggested channeling the waste heat generated by nuclear power plants to break down organic waste matter into compost. Creation of compost keeps the organic waste out of landfills, reduces methane emissions, and provides farmers with an inexpensive soil amendment.

COMMUNICATION

Three high-profile nuclear accidents—Three Mile Island, Chernobyl, and Fukushima—have created a profound sense of public mistrust in the nuclear enterprise. The three teams taking on IDR Challenge 4 had the opportunity to design and fund putative 3-year public/private initiatives to both understand and bridge the gap between public perception and the scientific realities of the nuclear enterprise.

Citing previously successful awareness campaigns in the fields of public health and the environment, all three IDR teams concluded that involving the public in decisions such as where to site new nuclear facilities—and giving them a realistic picture of the known risks—creates a sense of buy-in and trust. The teams also acknowledged the need to research baseline levels of public attitudes and specific areas of mistrust regarding the nuclear enterprise and compare those baselines to ongoing surveys to analyze the effectiveness of their interventions. Each team also discussed ways to educate nuclear science industry leaders and policy makers about the public's concerns regarding nuclear power and provide these individuals with effective communication training.

Each team took a different approach to communicating with the public. IDR Team 4A outlined the creation of an independent agency funded by the Nuclear Waste Fund called the "National Center of Nuclear and Radiation Communication" that would function as a nonpartisan source of public information. The center would organize town hall meetings, encourage nuclear utilities to interact with local communities, and develop new outreach tools such as video games, summer camps, massive open online courses, and TED talks.

IDR Team 4B considered a two-track approach to communicating with the public: a targeted education module for the K-12 age group and a public relations campaign for adults. Schoolchildren would receive hands-on lectures, field trips to local power utilities, and a high school–level Nuclear Science and Medicine course. The public relations campaign would rely on storytelling techniques, celebrity endorsements, and various mass media—books, viral YouTube videos, and Hollywood blockbusters.

IDR Team 4C imagined a program aimed at identifying 2,000 or so influential Americans who could be educated about the nuclear enterprise with the hope that these individuals could effectively convey what they've learned to their respective communities.

CONCLUSION

Participants in the 2013 NAKFI Conference on the Future of Advanced Nuclear Technologies engaged a broad range of scientific and political issues. Attempts to reconcile the high-yield, high-threat facets of the nuclear enterprise saw a handful of themes emerge throughout the final conference presentations, including the need for increased transparency (between the public and nuclear leaders as well as among nations), sharing (of both resources and responsibility), and simplicity (smaller, safer reactor designs and single-stream nuclear fuel cycles).

IDR Team Summary 1

Identify improvements in technology and other approaches that will ensure the future development and supply of radionuclides and radiopharmaceuticals for diagnostic imaging and therapy.

CHALLENGE SUMMARY

This challenge has several related parts: (1) Maintaining a reliable supply of Technetium-99m (Tc-99m) for single-photon imaging; (2) Availability and further development of PET radiopharmaceuticals; and (3) Expanding the supply of PET radionuclides beyond C-11, N-13, O-15, and F-18.

Technetium-99m is the workhorse of single-photon imaging. Its precursor is reactor-produced molybdenum-99 (Mo-99). Production of Mo-99 has a history of several problems: (1) Most has been produced by reactor irradiation of HEU, which has required the sole export of such materials from the United States. Alternative reactor production is available using LEU and there are now efforts to make this the only method of reactor production. (2) There have been a number of interruptions in the supply of Mo-99 as aging reactors have been removed from service. (3) U.S. supplies of Mo-99 have had to rely on foreign sources (Canada, The Netherlands, South Africa, etc.) and there has been considerable effort to develop a sustainable supply in this country (see American Medical Isotope Production Act of 2012). Also, there has been recent interest in alternative methods for the production of Tc-99m using accelerators, but issues of expense, specific activity, and distribution need to be addressed.

(Another radionuclide with desirable properties for single-photon imaging is I-123. This iodine isotope brings with it the advantages of halide chemistry and avoids the bulky coordination cage properties of technetium. In the past, its accelerator production had its own problems including cost, purity, and availability, but these seem to have been mostly solved. It has never enjoyed the anticipated uses predicted for it outside of iodide for thyroid imaging. Newly developed radiopharmaceuticals such as ioflupane [DaTscan™] might expand its utility.)

Radiopharmaceuticals labeled with positron-emitting radionuclides are now used to map a number of cellular functions including glucose metabolism, oxygen utilization, cell proliferation, amino acid uptake, and neurotransmitter status, to name a few. Produced, on-site, by cyclotrons capable of making Carbon-11, Nitrogen-13, Oxygen-15 and Fluorine-18 the most available compounds are primarily labeled with Fluorine-18 (F-18). This is partly due to its longer half-life (110 minutes) than the others and partly because of relatively facile fluorine chemistry. Carbon-11 labeled agents, despite the centrality of carbon compounds as biological substances, have been less used, in part because the short half-life (20 minutes) requires very rapid syntheses to produce pure products with high specific activity.

At present, there is a robust commercial supply of F-18 labeled FDG and NaF. Commercial supplies of other F-18 labeled compounds are severely limited. As a greater repertoire of tracers is developed for more specific diagnoses and monitoring response to therapy, the management of patients outside of academic medical centers is certain to be compromised unless an economic pathway for these can be developed.

In addition to the light elements (C, N, O, F), longer-lived positron-emitting radionuclides are likely to be desired for medical application. Some already showing promise are Cu-64, Zr-89, and I-124. These radionuclides are produced by cyclotrons or linear accelerators. Except for I-124, which can be used as iodide for thyroid studies, all need to be incorporated into complex organic compounds for imaging purposes.

For all medical imaging procedures there is a need to minimize the radiation dose received by patients without sacrificing diagnostic accuracy. The realization that medical imaging from CT and nuclear studies now represents the major source of public radiation exposure has mobilized the profession of Radiology into campaigns for minimizing exposure (*viz. Imaging Gently and Imaging Wisely*).

In addition to imaging, certain radionuclides are used for therapy. These include I-131 for thyroid disease, Sm-153 and Sr-89 for bone pain, Y-90 for liver metastases, In-111 and Lu-177 for neuroendocrine tumors. Newer ones, such as the alpha particle emitter Ra-223, have been used in research. Some are produced in reactors others in accelerators. For their full potential to be realized, continued availability of the radionuclides will need to be assured and specific delivery systems will need to be devised.

Key Questions

- Is the American Medical Isotope Production Act of 2012 sufficient to secure the continued need for Tc-99m? Should alternative methods of production continue to be pursued? Given the superior resolution of F-18 labeled agents, what advances in SPECT or CT technology will be required to justify the continued use of Tc-99m?
- As newer more specific PET agents are created, how will the manufacture and distribution of these be accomplished for use by other than major academic medical centers? The time for new agents to go from bench-to-bedside/clinic is quite a bit shorter in Germany and Japan than in the United States. What are the impediments to such transfer in this country, regulatory and otherwise, and how might they be eliminated?
- Is the use of radiopharmaceuticals labeled with longer-lived positron-emitting radionuclides likely to be employed other than in research? If so, how are they to be produced and distributed?
- As optimization of radiation dose in medicine becomes *dictum*, efforts will be made to use diagnostic nuclear medical studies appropriate to the clinical questions asked. In addition, technologies are, and will be, developed to reduce amounts of administered radioactivity without loss of diagnostic accuracy. What will these be, how much will they add to cost, and what are their limits?
- For a number of reasons, the use of radionuclides in therapy has been relatively restricted. What factors have limited their use (even when their efficacy has been demonstrated) and what might be done to overcome these hurdles?

Suggested Reading

Atcher RW. Medical radioisotopes—what steps can we take to ensure a secure supply? *Journal of Nuclear Medicine* 2009; 50(4):17-18N.

Congress passes American Medical Isotope Production Act. *Journal of Nuclear Medicine* 2013; 54(2):11N.

Fowler JS, Wolf AP. The synthesis of carbon-11, fluorine-18 and nitrogen 13 labeled radiotracers for biomedical applications. Nuclear Science series: NAS-NS 3201. National Technical Information Service: Springfield, VA, 1982.

Goske MJ, Applegate KE, Bulas D, et al. Image Gently 5 years later: what goals remain to be accomplished in radiation protection for children? *American Journal of Roentgenology* 2012; 199(3):477-479.

Hricak H, Brenner DJ, Adelstein SJ et al. Managing radiation use in medical imaging: a multifaceted challenge. *Radiology* 2011; 258(3):889-905.

Institute of Medicine. Isotopes for medicine and the life sciences. Report of Committee on Life Sciences, Division of Health Science Policy; National Academy Press: Washington, DC, 1995.

James ML, Gambhir SS. A molecular imaging primer: modalities, imaging agents, and applications. *Physiological Reviews* 2012; 92(2):897-965.

Kircher MF, Hricak H, Larson SM. Molecular imaging for personalized cancer care. *Medical Oncology* 2012; 6(2):182-195.

Mettler FA Jr, Bhargavan M, Faulkner K et al. Radiologic and nuclear medicine studies in the United States and worldwide: frequency, radiation dose, and comparison with other radiation sources—1950-2007. *Radiology* 2009; 253(2):520-531.

National Research Council. Medical isotope production without HEU. The National Academies Press: Washington, DC, 2008.

Peplow M. Technetium: nuclear medicine's crisis. *Proto* Summer 2013.

Sheehy N, Tetrault T, Zurakowski D, et al. Pediatric ^{99m}Tc-DMSA SPECT using iterative reconstruction with isotropic resolution recovery: improved image quality and reduction in radiopharmaceutical administered activity. *Radiology* 2009; 251:511-516.

SNM Position Statement on dose optimization for nuclear medicine and molecular imaging procedures. Society for Nuclear Medicine: June 2012.

Tu Z, Mach RH. C-11 radiochemistry in cancer imaging applications. *Current Topics in Medicinal Chemistry* 2010; 10(11):1060-1095.

Because of the popularity of this topic, three groups explored this subject. Please be sure to review the other write-ups, which immediately follow this one.

IDR TEAM MEMBERS—GROUP A

- Narasimhan Danthi, National Institutes of Health
- Patrick Hahn, Johns Hopkins University
- Efstathios Karathanasis, Case Western Reserve University
- Jason S. Lewis, Memorial Sloan-Kettering Cancer Center
- Michael A. McDonald, Johns Hopkins University
- Todd E. Peterson, Vanderbilt University
- Jonathan K. Pokorski, Case Western Reserve University
- Satish Viswanath, Case Western Reserve University

IDR TEAM SUMMARY—GROUP 1A

Patrick Hahn, NAKFI Science Writing Scholar, Johns Hopkins University

> "The poison is in the dose."—Philippus Aureolus Theophrastus Bombastus von Hohenheim, the father of toxicology.

IDR Team 1A was asked to identify improvements in technology and other approaches, such as educational initiatives and manufacturing and distribution plans that will ensure the future development and supply of radionuclides and radiopharmaceuticals for diagnostic imaging and therapy in the United States.

The team focused on four areas: the supply of stable isotopes, the availability of radioisotopes and tracers, translation of research from bench to clinic, and education.

Supply of Stable Isotopes

Stable isotopes are the starting materials needed to create the radioisotopes used for diagnostic nuclear imaging (SPECT and PET) and targeted radiotherapy, which are common in contemporary medicine. The major advantages of using enriched stable isotopes for radioisotope production are that purer, higher specific activity radioisotopes can be produced. The United States has relied on the isolation of stable isotopes using calutrons, but these currently are not being operated and have been in a standby mode since 2008. As a consequence, there is no domestic supply of these stable isotopes. A supply from international sources cannot be counted on indefinitely.

The team agreed that innovative technologies, including miniaturization of the cumbersome calutron technologies currently in use, are imperative to make the domestic manufacture of stable isotopes cost-effective once more. Public–private partnerships could help to make the adoption of these new technologies economically feasible, with public funding defraying startup costs, after which the day-to-day operations could be spun off to the private sector.

Availability of Radioisotopes and Tracers

The supply of radioisotopes and tracers available to clinicians is limited and inconsistent. The current centralized system is highly vulnerable to the failure of one of its components. Also, multiple tracers for the same target often make it to first-in-human use, with no clear first choice among them.

The vast majority of commercial cyclotrons are used to manufacture FDG, a radiolabeled glucose analog. This tracer is indeed a powerful tool in nuclear medicine, but focusing on this one tracer limits the availability of new tracers for clinical trials, making the approval of potentially beneficial new tracers a problem.

The United States needs a decentralized and coordinated infrastructure of cyclotrons to manufacture a variety of radiotracers for clinical use. The country needs a competitive but unbiased method to pick a winner among different radiotracers for the same target, making the commercial development and widespread distribution of that tracer economically feasible. The ultimate goal is the development of innovative single-stream technologies combining accelerators/reactors, separation, and radiopharmaceutical preparation for point-of-care application.

Translation to Clinic

The process of translation from lab bench to clinic needs to be streamlined. Before a New Drug Application can be approved, the applicants must submit data from all the relevant pathology and toxicology studies to the Food and Drug Administration (FDA). This information is called the path-tox package, and the burden of generating path-tox packages represents one potential barrier to translation. Another is poorly designed human trials without clear medical relevance or a well-defined endpoint. Finally, radiotracers may be approved by the FDA but not reimbursed by Medicare or Medicaid.

Radiotracers typically are administered in picomolar quantities, yet are held to the same safety standards as therapeutic agents administered in quantities many orders of magnitude greater. The process of generating toxicology studies could be streamlined by the increased use of existing data, and by the increased use of in vitro studies and/or computer modeling to reduce or eliminate the need for time-consuming and expensive animal studies. A nationwide database should be established to enable investigators to share data from path-tox studies, with the short-term goal of eliminating redundant trials and the long-term goal of eliminating the requirement for such studies for radiotracers altogether.

The cost of human trials could be reduced through smart trial design, with a well-defined clinical endpoint specified from the beginning. As therapies become increasingly specific for specific types of cancers, clinicians need to employ image-guided biopsies from the earliest stages of drug development in order to ascertain whether a given patient is expected to respond to a given drug before recruiting that patient to a trial. This in turn will make it increasingly difficult to recruit sufficient numbers of patients for a trial. In the future, multicenter trials will become the norm, in turn necessitating the development of new software to collate data from imaging studies, genomics, and proteomics from multiple centers, to help clinicians identify appropriate patients for different kinds of therapy.

A promising area of research is the new field of theranostics, or the combination of diagnostic and therapeutic entities into one drug delivery vehicle. All this should ultimately lead to greater quantitative precision in medicine as opposed to the current system of dosing according to body weight.

Finally, government agencies such as the FDA, National Institutes of Health, Nuclear Regulatory Commission, and the Center for Medicare and Medicaid Services need to work together at all stages of development of new radiotracers to facilitate reimbursement for approved radiotracers.

Education of New Workers

The average worker in the nuclear medicine field is 55-58 years old and the majority of the workforce is expected to retire within 10 years. The country is on the verge of losing an incredible resource, and little is being done to train new scientists specializing in this field. Few universities have programs in radiochemistry and nuclear medicine, and most have only a few students, scattered among different departments. Communication among different subspecialties relating to nuclear medicine is often poor.

The country needs programs to ignite young people's interest in nuclear science, such as the Department of Energy's recently closed Nuclear Summer School. Universities, professional societies, and government agencies need to work together to develop a curriculum enabling practitioners of all subspecialties relating to nuclear medicine to work together effectively. Studies are needed on the economics of radiopharmaceuticals. Finally, effective education/lobbying is needed to educate lawmakers of the benefits of nuclear medicine.

Conclusion

By means of all stakeholders working together, the full promise of nuclear medicine can be realized, resulting in improved patient outcomes at reduced costs.

IDR TEAM MEMBERS—GROUP B

- Sujata K. Bhatia, Harvard University
- Georges El Fakhri, Massachusetts General Hospital; Harvard Medical School
- Jacob M. Hooker, Massachusetts General Hospital; Harvard Medical School
- Julie L. Sutcliffe, University of California, Davis
- Yuan-Chuan Tai, Washington University in St. Louis
- Izabela Tworowska, RadioMedix Inc.; RITA Foundation Houston
- Frank J. Wessel, University of California, Irvine
- Julianne Wyrick, University of Georgia

IDR TEAM SUMMARY—GROUP 1B

Julianne Wyrick, NAKFI Science Writing Scholar
University of Georgia

IDR Team 1B was asked to identify improvements in technology and other approaches that will ensure the future development and supply of radionuclides and radiopharmaceuticals for diagnostic imaging and therapy. The challenge included several specific questions, such as how to manufacture and distribute new radionuclides for PET imaging so that they are available for widespread clinical use. Team 1B agreed that while these questions are very important, another fundamental issue must be tackled first—the need to develop radioactive imaging assays that are likely to be useful to the academic, clinical, and industrial communities.

The team identified two different approaches that could be used by imaging scientists to generate imaging assays with promise of value. The two approaches are the “bottom up” approach and the “top down” approach, as shown in Figure 1. The bottom-up approach refers to searching for new imaging agents by screening many potentially useful radionuclides. The top-down approach refers to first identifying clinical needs and searching for imaging agents to meet these needs. The team members emphasized that both approaches should be used.

They also noted that integrated training between academia and industry as well as between academia and the clinic must be used along with both approaches. For example, graduate students in the imaging sciences could benefit from spending a year in industry or a nonacademic clinical setting. Better partnerships among these three entities—academic institutions, clinics, and companies—are also needed to ensure the development of useful radionuclide imaging assays. The IDR Team noted that these partnerships should involve the commitment of money by all parties. However, the team chose to focus its discussion on the top-down and bottom-up methods of

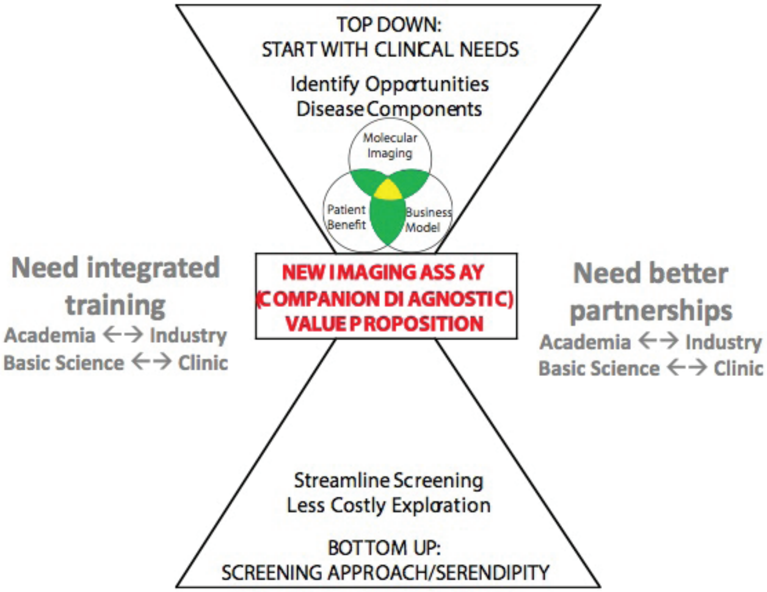

FIGURE 1 The two approaches that IDR Team 1B identified for developing imaging assays that would have promise of clinical, academic, and industrial value are shown. IDR Team’s strategies for improving these approaches are also shown.

discovery because another IDR Team was concentrating on the issues of training and partnerships.

Bottom-Up Approach

The first approach the IDR Team identified for generating imaging assays was the bottom-up approach, which is the approach traditionally used in scientific exploration. This approach could also be referred to as a screening approach. Specifically, it involves investigating many potential imaging agents and disease targets with the goal of identifying an agent-target combination that will be a high-value imaging assay for humans. The major challenge is the high cost of screening. The more radionuclides a researcher tests, the higher the cost. IDR Team 1B identified resources that could be shared to reduce costs, including labs, molecular libraries, synthesis methods, imaging protocols, personnel, and toxicology and pharmacokinetics data.

The IDR Team chose to focus in particular on developing a way to share toxicology and pharmacokinetics data. Currently, researchers must do toxicology and pharmacokinetics studies on potential radionuclide imaging agents when they submit an investigational new drug (IND) application before beginning clinical trials. Costs of studying imaging agents could be reduced if researchers did not have to repeat these studies for compounds that have already been studied by other researchers.

The IDR Team's strategy for sharing toxicology and pharmacokinetics data is the creation of a database called Free RIDES, an acronym for "Radiopharmaceutical + Imaging Database to Enable Sharing." The idea is based on the way protein sequences are already shared through public databases, such as the RCSB Protein Data Bank (PDB). When publishing a paper with data about a new protein sequence in a journal, researchers must submit the new protein sequence to a community-endorsed, public database. The team suggests a similar process when publishing studies that test a new radionuclide in humans for the first time. IDR Team 1B listed several key steps to achieving this goal. First, funding would be obtained for computing resources to create the database. Then, a prototype database would be built with volunteer contributions of toxicology and pharmacokinetics data for some number of radionuclides. For this process to succeed, NIH and FDA would be asked to require submission of these data to the Free RIDES database. Then, it would also be necessary to work with peer-reviewed journals to implement use of the database prior to publishing.

The IDR Team noted that there would be both short-term and long-term benefits of such a system. The short-term benefits would be for researchers applying for INDs for imaging agents. They could use the toxicology and pharmacokinetics database rather than having to conduct these studies again—a free ride. The system could reduce the time and money associated with studying imaging agents by approximately 2 to 4 months and drop the cost by approximately $200,000 per compound that received a "free ride." The long-term benefit would be the ability to build a scientific case to eliminate the need for toxicology and pharmacokinetics studies prior to clinical studies that involve microdoses of radionuclides. A microdose refers to a dose that is so low that it is unlikely to produce whole-body effects, as a therapeutic agents does. In other words, if toxicology and pharmacokinetics data consistently show no detrimental effects with microdoses of radionuclides, the requirement for these data to be obtained prior to applying for an IND could be removed.

Top-Down Approach

The second approach the IDR Team identified for developing useful imaging assays is the top-down approach, as shown in Figure 1. This involves starting with the clinical needs for imaging and then identifying radionuclide imaging agents to meet these needs. The challenge for this approach is identifying the principal components of many diseases, such as inflammation, for which imaging agents are needed. These disease components would identify areas of opportunity for developing new radionuclides that would have broad applicability. Then, research funding could be provided for studies seeking relevant imaging agents. The IDR Team developed a strategy to determine these components using an expert consensus panel.

First, the IDR Team suggested that a search for potential disease components be conducted using a mathematical approach. The components identified would later be used to begin discussion among a panel of experts. To conduct the initial search, publications and other disease data would be analyzed using a statistical procedure, such as principal component analysis, to identify commonalities among diseases. Conducting this analysis would first involve obtaining a grant to pay for the analysis. The grant would be publicized as a challenge grant, meaning people would submit algorithms for the analysis. The person with the best algorithm would receive the grant to conduct the analysis. The IDR Team suggested that once the principal component analysis was conducted, there would be an initial workshop and "request for comments" period in which stakeholders in the nuclear medicine community could give their opinion on whether the analysis identified the proper disease components.

Next, an expert panel would be assembled to further debate the disease components identified. Ultimately, the panel would identify several major disease components on which imaging research could be focused. The panel would develop a report on these high-impact areas so that funding for imaging assay research could be prioritized. Team 1B suggested that the panel include physicians, basic scientists, applied imaging scientists, business leaders, patient advocates, and regulatory body representatives. After the expert panel identifies the highest priority disease components, the IDR Team envisions that a funding body, such as the NIH, would develop grants for research of imaging assays addressing these components. Team 1B suggested a time frame of 2 years to complete the process of identifying disease components and allotting funding. Using this strategy, the chance of developing an imaging assay with both clinical relevance and marketability would increase, as research groups worked toward several main target areas.

IDR Team 1B's overall goal was to find ways to develop imaging assays with clinical, industrial, and academic value. Within this goal, they identified approaches that could be used to develop these assays: the bottom-up approach and the top-down approach. They also wanted to provide examples of innovative ways to improve these approaches. Specifically, these strategies included a toxicology database to reduce research time and cost, as well as an expert consensus panel to identify major imaging needs. Using these strategies to develop high-value imaging assays is an important way to ensure the future development and supply of radionuclides.

IDR TEAM MEMBERS—GROUP C

- Nsikan Akpan, University of California, Santa Cruz
- Richard E. Carson, Yale University
- Anthony J. Di Pasqua, University of North Texas System College of Pharmacy
- Michael T. Fasullo, College of Nansoscale Sciences and Engineering
- Sundaresan Gobalakrishnan, Virginia Commonwealth University
- Daniel A. Pryma, University of Pennsylvania
- Michael van Dam, University of California, Los Angeles
- Alan Waltar, Pacific Northwest National Laboratory
- Weian Zhao, University of California, Irvine

IDR TEAM SUMMARY—GROUP 1C

Nsikan Akpan, NAKFI Science Writing Scholar
University of California, Santa Cruz

IDR Team 1C was asked to identify ways that will ensure the future development and supply of radionuclides and radiopharmaceuticals for diagnostic imaging and therapy in the United States.

One challenge presented to the IDR Team is securing the domestic supply of technetium-99m (Tc-99m) and its precursor molybdenum-99 (Mo-99) in order to achieve nuclear medicine independence. The United States imports its entire supply of Mo-99 from a small number of overseas facilities.

The IDR Team disagreed with this directive, concluding that the time is ripe to alleviate nuclear medicine's Tc-99m reliance by focusing on the development of radiopharmaceuticals for positron emission tomography (PET) that do not require Tc-99m. They stated that if new PET radiopharmaceuticals are approved to replace Tc-99m radiopharmaceuticals, technetium would not be a major player in 10 years, with the SPECT industry outdated and not growing. This paradigm shift would obviate some consequences related to Tc-99m shortages and help safeguard the future success of the field as a whole.

Adopting a policy of domestic production of other isotopes could also answer the logistical dilemmas associated with purchasing Tc-99m abroad. Though President Obama ratified the American Medical Isotope Production Act in 2013 to protect the interests of nuclear medicine, more emphasis has been placed on phasing out enriched uranium rather than securing and stabilizing the medical isotope market.

The IDR Team agreed on four specific challenges that must be addressed to advance next-generation PET radiopharmaceuticals and nuclear science.

First, the desires of scientists, academic institutions, and the general public require better harmony. Current regulatory procedures unnecessarily stymie progress in nuclear medicine. A lack of coherent, consistent regulatory standards across government agencies, including the Food and Drug Administration (FDA), Centers for Medicare & Medicaid Services (CMS), and the National Institutes of Health, threatens innovation. The IDR Team proposed resolutions to expedite the bench-to-bedside journey for the most promising pharmaceuticals and for diagnostic tools solely for basic scientific discovery.

Second, a new dawn for radiopharmaceuticals will require fresh technology, with the IDR Team offering a list of the most pressing needs.

Third, recruiting the next generation of nuclear medicine professionals is critical, which was a concept that permeated throughout the NAKFI Conference. The IDR Team proposed a specific plan to encourage more young scientists to enter nuclear medicine.

Finally, education initiatives should be implemented to correct public myths connected to the safety of nuclear medicine.

The IDR Team ultimately developed a series of directives to tackle each hurdle, which they posited as the framework for a future policy statement to be issued by a major nuclear organization, such as the Society of Nuclear Medicine and Molecular Imaging.

Trial Harmony

Research institutions, scientists, the general public, and regulatory agencies aspire for radiopharmaceuticals to satisfy different objectives.

Research institutions have altruistic ambitions, but also must develop unique ideas that will bolster their reputations and attract young investigators. Scientists want freedom to make their developments accessible to as many patients as possible. Patients want safe, effective drugs as quickly as possible at the lowest costs. Regulatory bodies are charged with brokering those goals, while providing safety for patients.

Yet the development cycle for radiopharmaceuticals is long, expensive, and unnecessarily risky due mainly to shifting targets in the regulatory approval of nascent radiopharmaceuticals, according to the IDR Team.

They recommended holding a stakeholder summit where investigators, regulators, and institutional officials could discuss “trial harmony”—new guidelines to unify trial endpoints.

Regulatory cohesion

One major impediment raised during the meeting was shifting targets in the regulatory approval of radiopharmaceuticals. The two regulatory organizations in question are FDA and CMS.

Recent tribulations with Amyvid (^{18}F-florbetapir), the first FDA-approved PET radiotracer for Alzheimer’s disease, was offered as a prime example. Spawned from academic research, the tracer received FDA approval in January 2011, but patient access was ultimately denied by CMS last autumn. The decision represented a scary prospect for nuclear medicine, suggesting that heavy investments in the research and development of prospective tools may not be reimbursed at the end of the day. The average cost of inventing and obtaining FDA approval of a new drug is $1.3 billion, according to Eli Lilly, which now owns Amyvid and stands to lose up to $650 million across international markets. Moreover, patents and licenses are now vital revenue streams for many universities.

The IDR Team asked for more transparency with regulatory standards from the FDA and CMS.

The FDA's current regulations for investigational new drugs (INDs) and diagnostic agents were viewed by the team as another barrier. These rules require an imaging radiotracer to meet many of same standards as a therapeutic drug. This reasoning is unnecessarily stifling, in the team's opinion, because exposure to the radiotracer will likely be limited, relative to the use of an average drug. For instance, a person with heart disease might take a beta blocker every day for 30 years, whereas a PET imaging agent for cancer may only be used a handful of times for an individual patient. Furthermore, radiotracers are given in miniscule amounts, below the expected limits for any physiologic effects.

The team proposed expanding the FDA's Radioactive Drug Research Committee (RDRC) Program. This program permits human use of fledgling radiotracers, but without the heavy restrictions and costs of maintaining IND status.

Precision medicine is an arena that stands to benefit from these policy changes, according to the IDR Team, with companion diagnostics and theranostics given as examples. Companion diagnostics are assays that screen genes, mutations, or proteins and provide direct treatment strategies for a patient, while a theranostic is a diagnostic agent that can also be repurposed into a drug.

Pairing diagnostics with therapeutics tackles disease heterogeneity, while cutting costs. This is especially true with theranostics because the diagnostic agent often provides the molecular backbone for the drug, limiting the amount of time and effort invested in medicinal chemistry. Expanding the RDRC program could give scientists more freedom for basic research on companion diagnostic and theranostic radiotracers, while also unclogging the pipeline for drugs specifically destined for the clinical track.

Academic cohesion

A further ambition for the stakeholder summit is promoting greater academic cooperation within nuclear medicine. One problem within diagnostic imaging research is that individual scientists set their own standards for determining the sensitivity and specificity of new radioagents. This trend makes it harder to compare results among researchers studying radiotracers for identical biological targets.

The IDR Team recommended harmonizing trial endpoints to permit more prospective meta-analysis among laboratories working on similar classes of radiopharmaceuticals. The IDR Team cited the success observed with the Alzheimer's Disease Neuroimaging Initiative (ADNI), in which investigators across the world have partnered to collect findings on predetermined groups of imaging biomarkers for the neurological disorder.

The goal would be to unify the way scientists design their projects, produce gold standards for radiopharmaceutical validation, and gauge the best endpoints for clinical design.

Marquee example: prostate cancer PET imaging agents

Prostate cancer was posited as a promising realm for attempting trial harmony.

The principal test for the disease—serum screening for prostate-specific antigen—is prone to false positives with localized low-grade prostate tumors, leading to unnecessary biopsies. The assay also tends to miss small high-grade tumors, creating the opportunity for missed diagnosis. Finally, this testing gives little to no information on the location of the disease in the body (which can have significant implications on prognosis and optimal treatment strategy). More sensitive and accurate diagnostics are needed to guide therapy and measure clinical responses to cancer drugs.

PET radiotracers are gaining momentum as clinical tools for evaluating prostate tumor biology. ^{11}C-choline and ^{18}F-fluorocholine have garnered much attention in Europe and Japan over the past few years as lipogenesis markers. The former was approved by the FDA to detect recurrent prostate cancer in 2012, but the approval is currently limited to a single academic institution. The androgen-receptor tracer ^{18}F-fluoro-5α-dihydrotestosterone and ^{18}F-fluorodeoxyglucose (FDG) are in clinical trials as early-stage assessors of treatment outcomes, while other tracers are proving useful for staging or tracking bone metastasis.

Trial harmony and prospective meta-analysis could bolster this emerging field by unifying perspectives on which novel PET tracers should be pursued in earnest.

Future Technology for Nuclear Medicine

The IDR Team listed advances in technology that could help PET agents drive the modern era of radiopharmaceuticals.

The installation of small medical reactors and cyclotrons at more hospitals across the nation would facilitate the generation and testing of radionuclides for novel pharmaceuticals as well as PET mainstays such as ^{18}F-FDG. This would accelerate the synthesis, dispensing, and quality control of radioactive raw materials and radiopharmaceuticals for investigators. Furthermore, neutron-activation of radionuclides could be performed at hospitals, increasing the impact of this type of pharmaceutical, a specific example of which is TheraSphere. Evaluating new or rarely used isotopes for PET would also be aided by having more small reactors.

The emergence of microfluidics has made it possible to create accelerators on a microchip, and the IDR Team felt further investments should be made into microreactor technology. The broader incorporation of nanotechnology lends itself to developing fully automated pathways that reduce personnel costs and synthesis time for producing new delivery vehicles for radiopharmaceuticals.

Most of these concepts represent multidisciplinary challenges, according to the IDR Team, that do not fit under current funding opportunities from the National Institutes of Health and that were once, but no longer, funded by the Department of Energy. New avenues for support would be discussed at the summit.

Teaching Millennials About Nuclear Medicine

Two groups were spotlighted as important targets for education initiatives: young scientists and the general public.

The next generation of nuclear medicine scientists

No amount of innovation can replace bright minds, and a concern that loomed over the entire conference is the nuclear industry's aging population. Nuclear medicine is no exception, and the IDR Team reviewed recruitment strategies.

One fear is that students who could make contributions to this field are missing the chance because they are simply unaware of its existence. More programs that introduce undergraduates and recent graduates to concepts in radiation research were posited. Striking early could plant the seeds of expertise that bloom into basic research careers in nuclear medicine.

On the clinical side, the IDR Team said medical training programs need more synergy in their curricula. They described the typical medical university as having many nuclear disciplines or courses—for example, radiation oncology, diagnostic radiology, and nuclear medicine—but surprisingly little interplay between the programs of study. They would push for more interaction to streamline the education process.

The final suggestion involved the creation of a summer program for interested students. Dubbed the "theranostic boot camp," this program would provide hands-on experience and be geared toward reviewing the multiple disciplines involved with precision radiopharmaceuticals. North Carolina was suggested as a prime location for the camp, because NC State University runs a research reactor, while the University of North Carolina Chapel Hill has a renowned nuclear medicine program.

A new nuclear dictionary for the public

Public relations must improve for nuclear medicine, according to the IDR Team. Limiting radiation exposure is paramount feature of nuclear medicine, while many radiopharmaceuticals, especially diagnostic tracers, are safe and pose few health risks. Yet trepidation still filters into general attitudes toward radiation therapy and diagnostics.

A new vocabulary is needed so patients can comprehend radiation safety on their own. A visual lexicon, such as a color-coding system for risk levels, could provide a simple, but engaging solution.

IDR Team Summary 2

Develop a transformational fuel for Light Water Reactors—advanced and current.

CHALLENGE SUMMARY

The United States currently has 103 operating nuclear power plants producing over 100 GWe annually. These nuclear reactors are all light-water reactors (LWRs) and there are an additional six GWe of LWR capacity under construction. In the world today there are over 435 nuclear power plants, the preponderance of which are water-cooled reactors. There are also over 60 LWR nuclear plants under construction around the world including the United States. Given this situation and continued license renewals in the United States and in the world, it is safe to say that LWRs will be the dominant technology that is used to produce electricity from nuclear fission reactor plants for several decades.

There is a continued emphasis on improving the reliability and the safety of nuclear power plants. The accident at Fukushima reminded all of us of the need to stay vigilant and seek ways to improve the safety of both existing and new nuclear plants. Even though there were no fatalities from the accident, and its long-term health effects have been estimated to be far less than the tsunami, the economic impact has been huge and the release of radioactive materials off-site can have long-term environmental impacts in the region surrounding the site.

A direct way to improve the reliability and safety of current and future LWRs, is to focus on novel and transformative advancements in nuclear fuel and cladding design and development. This focus has the best chance of benefiting safety for current and future LWRs for decades.

It is important to consider strategic options, including time line and budget considerations, for accelerated development and widespread deployment of advanced fuel designs (fuel and cladding) for use in existing (and new) pressurized water reactors (PWRs) and boiling water reactors (BWRs), such that fuel integrity can be maintained in the event of anticipated operational occurrences, and design-basis accidents and the fuel rod is robust under beyond-design-basis conditions. This strategy must look broadly at improving fuel performance and safety; e.g., reduction in the generation of combustible gases during fuel degradation. The strategy could consider the use of modern scientific computational tools that could reduce the experimental and development time line and the steps required for validation of such advanced models. The costs and risks of implementing a new fuel design should be weighed against the costs and risks associated with engineering and administrative changes to the existing systems that could achieve a similar reduction in risk.

The challenge is to create a coherent plan for developing a novel fuel that incorporates the complete discovery-to-product process: i.e., R&D plan, fuel demonstration, reliable fuel manufacture, acceptance testing, and performance. This can also provide the opportunity to develop advanced fuels that take the entire fuel-cycle implications into account (e.g., spent fuel disposition) to improve upon the current circumstance in which fresh fuels are developed without regard to the implications for the rest of the fuel cycle.

Key Questions

Develop a transformational fuel for light-water reactors (advanced and current) that:

- Improves the safety performance for the fuel under the range of operating conditions (anticipated operational occurrences and load following), design-basis accidents (e.g., LOCA and post-LOCA behavior as driven by stored energy and cladding-coolant compatibility), and special events considered in licensing (e.g., minimized fuel failure in extended station blackout or ATWS, which may be more limiting due to differential responses between fuel and clad);
- Can be produced at a cost competitive with the current generation of LWR fuel (as an example, the total cost of a single fuel rod today is about $2500/kg and it produces about 50 MWDth/kg of energy);
- As secondary benefits, improves fissile fuel utilization, enhances

disposal options, and improves safety performance and reduces costs for spent fuel disposition."

IDR Team members are encouraged to explore ways fundamental advances in material science, nuclear fuels as well as computational modeling can help in these tasks. For example, there have been major advances in multiscale, multicomponent materials modeling that would allow for computational materials design and reduce trial-and-error experimentation. This could transform fuel and cladding design protocols and the novel fuel-clad system could improve behavior during operation and during more extreme environmental conditions.

Suggested Reading

Konings RJM, ed. Comprehensive nuclear materials, volume 3: Advanced fuels, fuel cladding and nuclear fuel performance modeling and simulation. Elsevier: Amsterdam, The Netherlands, 2012.

Nuclear Energy Agency. Nuclear fuel behaviour in loss-of-coolant accident (LOCA) conditions. State-of-the-art report. NEA-6846, 2009.

Nuclear Energy Agency. Nuclear fuel safety criteria. Technical review. NEA-7072, 2012.

Zinkle SJ, Was GS. Materials challenges in nuclear energy. *Acta Materialia* 2013; 61:735-758.

Because of the popularity of this topic, two groups explored this subject. Please be sure to review the other write-up, which immediately follows this one.

IDR TEAM MEMBERS—GROUP A

- Michael J. Fluss, Lawrence Livermore National Laboratory
- John J. Gantnier, Bechtel Power Corporation
- Peter Hosemann, University of California, Berkeley
- Kevin J. Kramer, Lawrence Livermore National Laboratory
- Wei Lu, University of Michigan, Ann Arbor
- Digby D. Macdonald, University of California, Berkeley
- Brad Marston, Brown University
- Vikas Prakash, Case Western Reserve University
- Naveena Sadasivam, New York University
- Marius Stan, Argonne National Laboratory
- Brian D. Wirth, University of Tennessee

IDR TEAM SUMMARY— GROUP 2A

Naveena Sadasivam, NAKFI Science Writing Scholar
New York University

Evolutionary Approach to a Transformational Fuel

IDR Team 2A was asked to formulate a coherent plan for developing a novel fuel for light-water reactors (LWR) that incorporates the complete process from discovering a fuel to producing it.

More than 80 percent of the 435 nuclear reactors worldwide fall into the category of LWRs. Known for their simplicity and comparatively low construction cost, LWRs are currently the most widely used type of nuclear reactor and are slated to remain the “go to” type of reactor in the coming years. In the United States, all of the 103 nuclear reactors are LWRs.

A majority of the technological advances that made the LWR cost- efficient, safe, and reliable took place in the 1970s and 1980s. Given the ubiquity of the LWRs and their slow technological development, it is befitting then that Team 2A worked to create a plan to develop a new fuel that is safer and more efficient.

Scope of Discussion

Team 2A agreed that it needed to suggest a solution that can be maintained in the event of anticipated as well as unanticipated accidents like those at Fukushima and Three Mile Island. While unanticipated events are rare, their consequences can be catastrophic and so it is important to factor them into design considerations. Therefore, the team concluded that because it is impractical to design fuel that can withstand the most catastrophic accidents, it could instead design fuel with a slightly different objective in mind—to provide the plant operator more response time.

Furthermore, the cost and practical implementation of introducing a new source of fuel to existing and new reactors must also be considered. If the nuclear reactor industry finds that the changes from the status quo are too drastic, it might reject the solution as a whole. An extremely safe solution might also be too expensive for the industry to adopt. Thus, the team will need to strike a balance between market feasibility and safety.

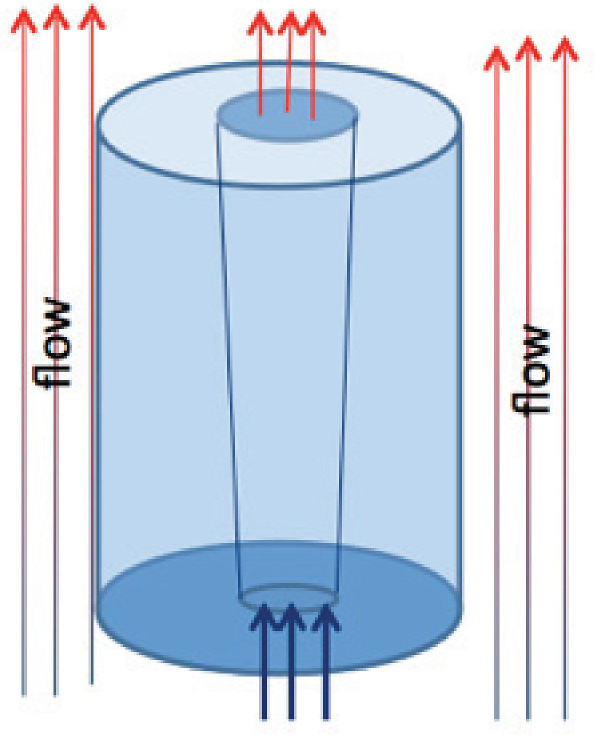

FIGURE 1 An annular fuel rod with two pathways for the flow of water will increase energy efficiency.

Annular Fuel Design

A typical fuel rod used in nuclear reactors consists of small pellets of enriched uranium in the form of uranium dioxide that is then placed into tubes of zirconium alloy. Bundles of 14 × 14 or 17 × 17 tubes of enriched uranium are assembled together with space in between for the coolant—water—to flow through and transfer heat.

Team 2A proposed an innovative type of fuel rod that allows the coolant to flow both within the fuel rod itself as well as around it.[1] Figure 1

---

[1] Zhang, L. Evaluation of high power density annular fuel application in the Korean OPR-1000 reactor." MS thesis, Massachusetts Institute of Technology, 2009; Morra, P., Design of annular fuel for high power density BWRs. MS thesis, Massachusetts Institute of Technology, 2004.

is a diagrammatic representation of the annular fuel rod that the Team designed. The inner diameter of the rod is not constant and is instead tapering outward. The water that enters at the bottom of the rod will be at a low temperature. As it moves through the inner pathway, it will absorb heat from the rod and exit at a higher temperature. Similarly, the water flowing along the outer surface of the rod will also experience a similar temperature increase. For pressurized water reactors, the flow rate of water can be adjusted so that it does not form steam. Since the coolant flows through the annulus and on its surface, it is expected that heat transfer will be faster and that it will increase energy efficiency.

The team also proposed that the gas-filled gaps that are usually present within the rod be replaced with porous graphite foam. By engineering the porosity of the pellets, channels can be formed for the fission products so that there is uniform accumulation of gas along the length of the rod. This will keep the geometry of the rod constant but change the pellets at a microscopic level. The team initially suggested that a fission gas vent be installed to deal with buildup of gas pressure, but because of a high risk of mechanical failure and drastic change to the entire reactor structure, the idea was discarded.

One other variation of the annular fuel rod design discussed was to have a matrix of four or six sets of fuel pebbles enclosed within an annular cladding. The team felt that this would provide sufficient thermodynamic stability but that the optimal number of fuel sets would need to be determined through simulation and experimentation.

Pathway to a Transformative Fuel

To develop a fuel that fundamentally transforms the nuclear industry by providing higher energy efficiency and better safety, the team believes that it will take several incremental steps over a long period of time for both innovation in nuclear engineering as well as development of new materials used in fuel rods. Short of an enormous political and societal will to mainstream nuclear reactors, the team believes that the series of iterative events outlined in Figure 2 are required to develop a new transformational fuel. These steps provide both the required time and allocation of resources required to complete the process.

On the engineering side, researchers need to first analyze and test the current LWR system and identify areas where optimization is feasible. At the same time, material scientists will need to begin by testing materials to

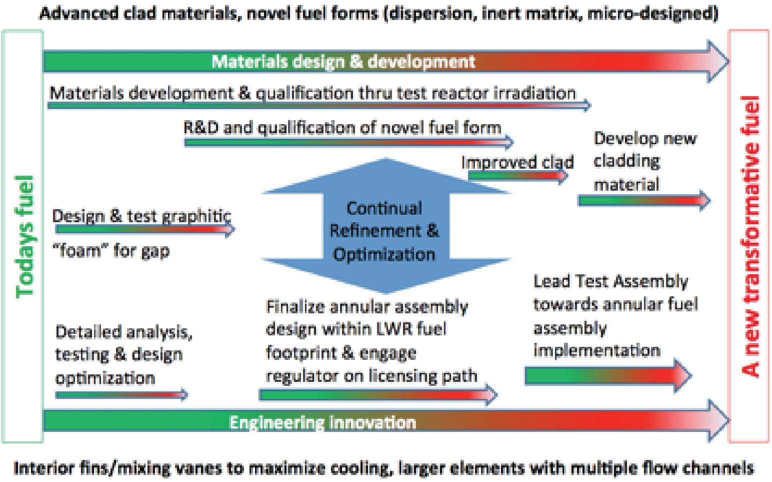

FIGURE 2 Steps to be taken in the engineering and materials research that will lead to the design of a new transformative fuel.

observe how they respond to different levels of radiation and then identify suitable substances that can be used. Once the initial research stage is complete, the annular fuel assembly design will need to be finalized and then submitted to regulators for licensing. To produce a truly revolutionary fuel, the cladding used in the system will also need to be improved. Hence, the cladding materials research will need to continue until a new type is developed. Once this is done, a lead test assembly will need to be conducted in order to identify implementation issues and assess the overall efficiency of the LWR.

The ideas listed above are by no means a complete list of work that needs to take place before a new fuel is on the market. The Team anticipates that the process will take several iterations and effective communication between the materials and engineering researchers to coalesce at a fundamentally transformative fuel for LWRs.

Research and Future Development

The IDR Team has also identified four key areas that require additional research work.

1. Multiple flow channels: Increasing the number of flow channels within the fuel assembly can help optimize power density, thermal hydraulics, and manufacturability.

2. Materials development: The current zirconium-based cladding needs to be replaced by advanced clads that have reduced oxidation kinetics.

3. Evaluation of alternative fuel forms: Inert matrix fuels such as TRISO and CerMet need to be analyzed. Micro-engineered porosity or engineered composite fuel forms are also alternatives to be considered.

4. Reactor-fuel-coolant concepts: There is a need for LWR concepts that reduce the high-power density and water use while also providing flexibility to meet the challenges with the back end of the fuel cycle, including the possibility of finding fuels that can be reprocessed in an economically viable way.

IDR TEAM MEMBERS—GROUP B

- Stephen T. Bell, Office of Naval Reactors
- Jeremy T. Busby, Oak Ridge National Laboratory
- Annalisa Manera, University of Michigan
- Martha L. Mecartney, University of California, Irvine
- Amit Misra, Los Alamos National Laboratory
- Jodi Murphy, University of Georgia
- David Petti, Idaho National Laboratory
- Mitra L. Taheri, Drexel University
- Bernhard R. Tittmann, Penn State University
- Steven J. Zinkle, Oak Ridge National Laboratory

IDR TEAM SUMMARY—GROUP 2B

Jodi Murphy, NAKFI Science Writing Scholar
University of Georgia

IDR Team 2B was tasked with the challenge of developing a transformational fuel for light water reactors (LWRs)—advanced and current.

Background

The 100 nuclear power plants operating in the United States are all light-water reactors. They produce more than 98 gigawatts of electric power

(GWe) annually. Six more GWe of LWR generation is under construction in the United States and will be available after current construction is completed. LWRs are likely to be the primary technology used to produce electricity from nuclear fission reactor plants in the coming decades. Most of the 436 nuclear power plants worldwide are water-cooled reactors. The number will soon grow, as more than 60 LWR nuclear plants are under construction throughout the world, including those being built in the United States.

The current widespread global use of LWRs for power production and the Fukushima accident in 2011 have led to many investigations, including tsunami tolerance and the ability to provide reliable backup power or tolerate a loss of site power. One area of investigation has been to consider the potential to develop an advanced fuel for LWRs that can better tolerate the high-temperature environment that can exist during an anticipated operational occurrence or an accident, without releasing large amounts of radioactivity from the fuel.

The IDR Team met to develop a conceptual approach for creating a novel fuel that incorporates the complete discovery-to-product process. This plan examines the R&D that would be needed, demonstration of the safety and effectiveness of a new fuel, reliable fuel manufacture, and performance. Industry acceptance would also be taken into account. A thorough and comprehensive plan would have to be created by a larger team over several months. A thorough analysis might also prompt the development of advanced fuels that take the entire fuel cycle implications into consideration in order to improve the current circumstance in which new fuels are developed. Notionally, a transformational fuel should have the following general characteristics to be successful:

- Decrease the risk of fuel failure and radioactivity release over the full range of operating conditions, including anticipated operational occurrences, load following, design-basis accidents (such as loss-of-coolant accidents [LOCAs]), and loss of decay heat removal accidents such as station blackout).
- Be cost-effective with current fuel in LWRs. For example, the total cost of a single fuel rod today is $2500/kg, and this rod produces approximately 50 Mw-d thermal/kg of energy.
- Should not significantly degrade fuel utilization and burnup efficiency (i.e., introduce excessive neutron absorbers) and should improve fissile fuel utilization if practical. It is desirable to improve reactor performance characteristics such as energy density or power density, increase options for

fuel disposal, and reduce operating costs. Early, comprehensive engineering design and business case assessment need to be done to ensure that candidate nuclear fuels have the promise to become practical and ecomomical reactor fuels.

The team considered ways to use fundamental advances in material science, including nuclear fuels and computational modeling, that can aid in materials design. Modeling methods exist to calculate some material properties, such as thermodynamic properties, and to predict the effects of material behavior on fuel element behavior or reactor performance. These methods can help reduce trial-and-error experimentation in developing new fuel materials and concepts. This may aid in designing alternative fuels with improved behavior during operation and during more extreme environmental conditions. Integrated behavior of new fuels will still have to be established by prototypic testing in, for example, a test reactor environment prior to operating a new fuel in a power reactor, since analytical techniques alone are not sufficient to describe the complex interactions of phenomena within nuclear fuels during operation.

In determining how to develop a transformational fuel for LWRs, the time line and budget must be handled strategically in order to accelerate the development and deployment of advanced fuel and cladding designs to be used in existing LWRs and new pressurized water reactors (PWRs) and boiling water reactors (BWRs). This foresight will enable fuel integrity to be maintained in the event of any breakdowns in operations. Safety must be a top consideration in the improvement and innovation schemes. Contemporary scientific computational tools may decrease the experimental and developmental time line, as well as the steps necessary to validate advanced models. The potential negative impact of instituting a new fuel design must be compared to the potential consequences of engineering and administrative changes to the existing systems that may achieve a similar decrease in case of a threat of danger.

Discussion

The team incorporated perspectives of both mechanical engineers and materials engineers. The mechanical engineers considered the problem from the angle of assessing the how the reactor would function as a whole. Their opinions hinged on practicality and the effect of new materials on overall reactor design, operations, and maintenance from a systems perspective.

The materials engineers had aspirations of creating ceramic and/or metallic materials to coat the fuel pellets and/or cladding to improve the safety of the LWRs.

Another possibility that the team considered was the potential to replace LWRs entirely with a new type of reactor that is inherently more tolerant of accident conditions. The team acknowledged that this is a remote possibility for many reasons, such as the cost. For example, new clear reactor design projects are multi-billion-dollar programs executed over a decade or more, and construction costs can be several billion dollars per unit. The United States lacks the manufacturing infrastructure needed to make rapid changes needed to replace LWRs entirely and does not face the pressing lack of electricity that nations such as China and India do. In addition, there is widespread distrust and misunderstanding of nuclear power in the United States. It may be more likely that alternative reactor concepts will evolve in parallel with any efforts to upgrade the fuel in LWR plants. If practical, it would be desirable for development of a new fuel for LWRs to provide a springboard for development of advanced, more resilient nuclear power plants.

The team agreed on some characteristics of the ideal alternative fuel, which also addressed the ideal cladding system. It must be compatible with steam and liquid water over 280-1000 degrees Celsius. It must be hermetic to fission products and water. It must have high strain to failure and linear elastic behavior up to the stresses to about 18-20 ksi to allow for practical mechanical design. However, the materials must also be tolerant of changes in fuel or structures under neutron and gamma irradiation (e.g., fuel swelling and stress-free growth). A fuel cladding material must have substantial toughness because of inevitable manufacturing defects. It needs to be a nonneutron absorber. It must be manufactured with practical industrial and chemical processes. It should be corrosion resistant and in a form that lends itself to disposal. It must have fuel, clad, and structural compatibility and be compatible with the full fuel cycle.

Development Challenges and Constraints

Development of a new, accident-tolerant LWR fuel is a major, multidisciplinary effort with potentially high consequences if a new fuel is put into service and does not work as anticipated. The total costs of producing a new LWR fuel are likely on the order of $1 billion. Strong, central technical leadership would be essential to align and coordinate a diverse group of scientists, engineers, manufacturers, regulatory interfaces, etc. There should be one person and organization responsible for providing technical leadership, coordinating all activities, making final technical decisions, and providing accountability to government regulatory agencies. The organization should be composed of professional R&D and materials test groups, major infrastructure operations, design engineering, fabrication vendors, regulatory review and standards (such as the Nuclear Regulatory Commission), and a commercial customer for an operational test in an existing commercial reactor.

Risk tolerance is necessary for the timely development of new materials. There must be a parallel test, design, and fabrication completed on a short time line, which requires decisive actions with limited information. The risk can be mitigated by simultaneously pursuing multiple options—in other words, having back-up plans. Rational risk mitigation would also involve conservative design and removal of the test assembly prototype.

Conclusions

The IDR Team devised an optimum time line in which a new fuel and cladding system could be developed, tested, and implemented. The project would require a huge financial investment up front that would need to be justified based on a compelling vision of improving operating reactor safety. It would be desirable to demonstrate the potential for long-range economic benefits from reducing power plant operating or maintenance costs.

The time line is representative of the likely course of events. In years 0-5, low-level lab assessment, including scoping studies, computational models, and early materials testing would occur. During years 2-20, the product would be licensed and energy companies interested in purchasing the new fuel and cladding system would be sought out. Years 6-12 involve finding investors and performing testing to garner more complete materials data needed to engineer a fuel assembly. In years 4-20, irradiations would be conducted. Years 4-7 are for the preconcept stage, 7-9 are for the concept stage, 8-10 are for the reference stage, and 9-20 are the final stage. In years 7-10, the first manufacturing trials would be conducted to scale up and determine the details of the design. During years 9-12, the fabrics used would be qualified, and during 10-13 the facilitization would be conducted. In the final 12-18 years, the fabrication and testing of a prototype set of fuel assemblies would go on.

The IDR Team estimates that if the time line were accelerated to occur at optimal speed, the entire process from concept to actualization and testing could happen in 12 years. This would require robust and stable funding to initiate and complete research, as well as increased tolerance for risk in government-funded research, so that activities could proceed more in parallel to shorten the development time line.

The alternative fuel and cladding system must have enhanced retention of fission products. To improve fuel containment of fission products, the IDR Team suggested minimizing fuel relocation and dispersion, lowering operating temperatures, inhibiting clad internal oxidation, and an increased fuel melting safety margin. This will also be accomplished through improved cladding, which will help maintain core cooling and retain fission products. Improved cladding could be created through improved high-temperature clad strength and fracture resistance, increased thermal shock resistance, greater high-temperature compatibility, and resistance to hydrogen embrittlement.

The IDR Team identified multiple concepts for a transformational fuel for LWRs. The materials-based solutions include enhanced confinement of fission products near their origin, perhaps microencapsulated dispersed fuel forms to provide more robust containment of radioactivity in the fuel. Improved cladding with high-temperature oxidation resistance in the stream and improved chemical reactivity were suggested. Other materials-based solutions included woven and engineered composite systems, made of either metals and/or ceramics interwoven for strength, ductility, and oxidation resistance. Other possibilities include fully ceramic, ductile nanograin materials. Engineering- and physics-based solutions included passive heat removal systems for severe accident conditions or modified fuel forms such as annular fuel that could provide more efficient heat transfer from the fuel to the coolant.

IDR Team Summary 3

Develop innovative approaches to make special nuclear materials (SNMs) more easily monitored and more detectable if stolen.

CHALLENGE SUMMARY

The United States, as well as several other countries, expends considerable resources to protect stored special nuclear materials (SNMs), as well as to detect such materials if stolen or transported internationally. Especially if enclosed in high Z shielded containers, Pu, U and other transuranic materials are extremely difficult to detect in the normal flow of commerce. Radiation monitors are deployed at great expense at land border crossings and points of air and sea embarkation and debarkation in attempts to detect smuggled materials. Although effective for some contraband radioisotopes, these monitors tend to be relatively ineffective as a detection approach for small quantities of SNMs. New approaches continue to be worked on that promise to improve the detectability of these materials. More specifically, new means of probing specific signatures of nuclear materials are being developed that could enhance the detection probability of such materials while reducing the number of false alarms. For example, photon beams that excite specific states in the materials of interest promise to enable the detection and quantification of materials even for standoff distances with minimum impact on the environment. As a passive technology, muon tomography has offered real promise. But can such systems be developed and built with sufficient sensitivity and with a footprint feasible for realistic operations at isolated borders or in mainstream commerce?

The locations of the vast majority of stored SNMs are known and are in reasonably secure locations in several parts of the world. Assume that international agreements could be successfully negotiated that require creative, new configurations for storing SNMs. What innovative approaches could be developed and deployed that would make these materials more easily monitored and more detectable if stolen (e.g., tagged with coatings of detectable isotopes or with detectable gases that would be emitted if containers are breached?). What approaches could make these materials more easily traceable and less useable if they fell into the wrong hands?

SNMs are most likely to be with us for the foreseeable future. There are several international institutions and agreements that are in place to help manage the risk. Arguably these have been successful in preventing wider proliferation of nuclear materials as well as accidental or intentional nuclear events. But it is not clear how long this situation with continue.

Key Questions

- What are the scientific and practical limits of the detectability of SNMs?
- What new technologies to detect SNMs are under investigation and can they be practically developed and deployed nationally and internationally?
- In addition to technical performance and cost, what other criteria (e.g., radiation dose to operators, existing international agreements, host state motivations) must be considered in selecting detection technologies for deployment?
- What are the institutional barriers to international "requirements" that SNMs be more detectable and/or less usable?
- Since SNMs are likely to be with us for a long and unpredictable length of time, what are suggested improvements to international institutions to manage the risk?
- Given the grave consequence of a failure to manage the risk, are efforts in training specialists adequate?

Suggested Reading

IAEA safeguards agreements and additional protocols: non-proliferation of nuclear weapons and nuclear security. International Atomic Energy Agency, April 2005.

IAEA safeguards agreements and additional protocols: verifying compliance with nuclear non-proliferation undertakings. International Atomic Energy Agency, September 2011.

NNSA next generation safeguards initiative fact sheet. U.S. Department of Energy, National Nuclear Security Administration, Jan. 2, 2009.

Nuclear energy research and development roadmap: report to Congress. U.S. Department of Energy, April 2010.

IDR TEAM MEMBERS

- Brandon P. Behlendorf, University of Maryland, College Park
- Peter C. Burns, University of Notre Dame
- Jacinta C. Conrad, University of Houston
- Julia R. Greer, Caltech
- Jie Lian, Rensselaer Polytechnic Institute
- Jessica Morrison, Freelance Writer
- Shriram Ramanathan, Harvard University
- William C. Regli, Drexel University
- Kenan Unlu, Pennsylvania State University

IDR TEAM SUMMARY—GROUP 3

Jessica Morrison, NAKFI Science Writing Scholar
Freelance Writer, Washington, DC

IDR Team 3 considered innovative approaches that would make special nuclear materials (SNMs) more easily monitored and more detectable if stolen. After identifying problems and potential areas for technological development and implementation, IDR Team 3 established grand challenge areas (materials, technology, and systems) and self-selected into expertise groups to strategize ways to gather background information and develop potential solutions. Defining the grand challenge also included identifying problems with the current SNM monitoring and state-of-the-art detection.

What Are Special Nuclear Materials (SNMs)?

Since the end of the Cold War and the break-up of the Soviet Union in the early 1990s, the control of nuclear materials has been a strategic and costly necessity for nuclear nations bound by the Non-Proliferation Treaty (NPT), to which the United States is a signatory. Among its challenges is a requirement that signatories maintain control of radioactive materials that may be used as explosive devices or used to create nuclear explosive devices.

Special nuclear materials, as defined by Title I of the Atomic Energy Act of 1954, are "plutonium, uranium-233, or uranium enriched in the isotopes uranium-233 or uranium-235." These are materials formed in nuclear reactors or extracted from used nuclear fuel that can be recycled to manufacture nuclear explosive devices with or without transmutation or further enrichment.

Problems with Current State of the Art

Although monitoring at border crossings and ports of entry exists for radioactive materials, the passive detection methods widely deployed in these locations often lack the sensitivity to detect small quantities of SNMs shielded by lead or even water. The sensors are fixed in place and may require detection times as long as 10 hours for shielded materials. The IDR Team recognized these and the following as problems with the current state of the art:

- Deployment of detection and monitoring techniques is not standard worldwide.
- Variations in worldwide background radiation mean SNMs could slip through undetected.
- High false alarm rates encourage security personnel to turn off detectors.
- Active interrogation by imaging or detection of high-energy gamma radiation is expensive, limited in availability, and may pose privacy and public health concerns.
- Current detection technology doesn't provide enough information efficiently and there is no integration with other critical sources of information, like geospatial tracking devices.
- After SNMs are detected, there is no direct pathway for identifying a material and its source.
- The pathway from technology development to implementation is slow and cumbersome.

Detecting the 1 Percent: Challenge Area Priorities and Recommendations

IDR Team 3 identified three challenge areas—materials, technology, and systems—and self-selected into groups based on expertise to gather background information and propose solutions to challenges determined by the larger group. Two groups formed—materials/technology and systems—as members of the materials and technology groups chose to combine.

Materials/technology

Ninety-nine percent of SNMs are located securely in known locations worldwide. The materials/technology group asked, "How do we protect, detect, and identify the 99 percent of SNMs that we know about?" The group focused on physical tagging and/or chemical modification of this majority group of SNMs to make them more easily detected in the case of loss or theft. Specific actions included increasing the opportunity for detection by modifying a material to produce a dynamic signal that is chemical, electrical, or thermal; using existing GPS or radar technology within packaging that emits an alarm and transmits identifying information when movement is detected; and considering additional tracking mechanisms to provide built-in redundancy.

The detection of illicitly trafficked SNMs, the 1 percent, currently relies on technologies at border crossing that cannot detect small quantities of highly shielded materials. The materials/technology group asked itself, "How do we protect, detect, and identify the 1 percent of SNMs that we don't know about?" The group focused on increasing the sensitivity of detection, identifying transformational uses of current technologies, and tracking motion with lasers and infrared. Specific actions included moving away from detection via alpha and/or gamma particles or creating a detection method that would excite or amply these traditional signals; improving existing and developing new technologies to better detect shielded material using thermal and imaging methods; and integrating detection systems with cell phones using thin-film technology.

Systems

The systems group considered the role of game theory, institutional and sociocultural barriers, environmental solutions, the balance between security and detection, the insider threat, and the role of intelligence and deterrence as a way of modeling the adversarial threat. "Instead of trying to find the needle, remove the hay," said one team member. The systems approach concerns the 1 percent of SNMs that are not securely stored.

Threat modeling of illicitly trafficked SNMs requires understanding a widely distributed and ever-changing adversary. Detection, too, should be imagined as a complex, adaptive system that is widely distributed. The systems group considered specific actions including moving away from fixed sensors and toward cheap, small, mobile, and widely distributed sensors for detection; addressing false alarms by requiring multiple alarms for detection; developing new methods to analyze and refine the distributed network detection system; and creating a network of worldwide background radiation profiles. Further, adoption by states, agencies (taxi drivers, for example), and individuals (as nodes in the system) would enhance detection capabilities.

Expected Impact

An integrated approach to protecting, detecting, and identifying SNMs that considers materials, technology, and systems is expected to create a more complete operational picture of material status and those adversaries who would attempt theft, transport, sale, or unauthorized use of SNMs.

Improving existing infrastructure by the addition of enhanced sensors, remote detection, specially designed shielding containers that respond to motion, and a networked systems approach would make better use of existing resources, enhance detection, and reduce costs. Although challenges exist in sensor design, information integration, technology adoption, and any number of unknowns (e.g., as yet unimagined countermeasures to detection), progress toward making the world safer against threats from the illicit use of SNMs may be enabled through improved effective use of existing technologies, the inclusion of a well-connected public in problem solving, and the development of new benchmarks for success.

Conclusions

SNMs will be with us for the foreseeable future. Prior and current initiatives to control and detect SNMs have been expensive and time-consuming while doing little to advance the technology needed to sufficiently secure nuclear materials. An integrated approach that considers innovations in materials, technology, and systems is central to the solutions recommended by IDR Team 3. If successful, such an approach would make better use of existing resources, enhance detection, and reduce costs. The benefit to society is great—a world free from nuclear threat at the hand of rogue actors.

IDR Team Summary 4

Design and fund a 3-year public/private initiative to better understand and bridge the perception/reality gap between the public and nuclear experts on the risks of the nuclear enterprise and to restore the public trust.

CHALLENGE SUMMARY

Fifty years ago, approximately half of the general U.S. population believed that a nuclear reactor could explode like a nuclear weapon, though this is physically impossible. In light of Chernobyl and Fukushima, it would not be surprising to find that at least half of today's population would believe the same and not trust assurances of experts to the contrary. In fact, these and other disasters, the lack of an implemented waste solution, and other problems have made early and continued assurances by the nuclear community as to the outstanding safety, security, and environmental record of nuclear power ring hollow to many.

Much the same can be said of nuclear risk-related communication programs. This lack of "better understanding" comes in spite of many efforts in the succeeding decades by the industry and nuclear scientists to communicate the risks in a clearer more compelling fashion. This continues to hamper and introduce uncertainty into the nuclear power industry. There is much to be learned by the public, but there is also much to be learned by the nuclear community about risk communication and the development of public trust.

Today there is no operating repository for the permanent disposal of spent nuclear fuel and high-level radioactive waste anywhere in the world. The U.S. program, to develop and license the Yucca Mountain, Nevada site in the United States was brought to a halt in part due to unrelenting political and public opposition. But significant progress is being made elsewhere in the world and we can expect to see operation of the first such repositories in Finland and Sweden in the coming decade or so, and France and Canada are making substantial progress after stopping and recalibrating their programs. We have also seen the continued success at the Waste Isolation Pilot Plant (WIPP) in Carlsbad, New Mexico, where transuranic (not high-level) wastes from defense-related activities have been disposed in a program that has now gone on for over a decade and leaves the host community asking for a broader waste mission.

The resistance to nuclear technology among the general public springs from a variety of reasons. People are often highly emotional and afraid of the risks of radiation while they will have an X-ray or take a transcontinental flight without a second thought. Explanations of relative risks by experts are often conflicting, difficult to understand, and caveated by scientists in ways that undermine confidence. The classic NIMBY reaction is also much in evidence as people are both afraid of having nuclear facilities nearby and worried about the stigma effect that can have real or perceived impacts on their lives.

The differences in public trust and public acceptance for nuclear medicine and nuclear power are stark and enormous. The U.S. public has been accepting more and more radiation exposures in medical treatments over the past two decades with little resistance while the public reaction to the siting of nuclear power facilities and nuclear waste management facilities, in particular, has been fierce. What lessons can be learned by each community from the experiences of the other? What can we learn from the success of others?

The challenge is for the nuclear community to understand that the resistance is not the public or the media's fault and to fashion a different way of engagement and communication to bridge the gap in ways that may inform the nuclear community as much as the public.

Key Questions

- What do we know about the U.S. public's appreciation and understanding of nuclear technology and the associated risks? What can we learn from public acceptance of increasing medical exposures?
- What do we know about risk communication writ large and how can these lessons be applied to the nuclear enterprise?
- What can we learn from public acceptance of nuclear in other nations and in successful U.S. programs?
- How have programs in the United States and abroad dealt with en-

hancing public trust and confidence and what lessons can be learned from their successes and failures?

- Can we design an initiative that invites in a broader constituency of expertise related to the topic with the objective to not only improve risk perception among the general public but improve risk communication among the nuclear community? Can we tie this to a better understanding of not just what is communicated but how the engagement process works to improve public understanding and public acceptance?

Suggested Reading

Report to the Secretary of Energy. The Blue Ribbon Commission on America's Nuclear Future, 2012.

Choosing a way forward: the future of Canada's used nuclear fuel. The Canadian Nuclear Waste Management Organization, 2005.

Dunlap RE, Kraft ME, Rosa EA, eds. Public reactions to nuclear waste: citizen's views of repository siting. Duke University Press: Durham, NC, 1993.

Freudenburg WR, Rosa EA, eds. Public reaction to nuclear power: are there critical masses? Westview Press for the American Association for the Advancement of Science: Washington, DC, 1984.

Jenkins-Smith HC. Public beliefs, concerns and preferences regarding the management of used nuclear fuel and high level radioactive waste. Report for The Blue Ribbon Commission on America's Nuclear Future, February 2011.

National Research Council. One step at a time: the staged development of geologic repositories for high-level radioactive waste. The National Academies Press: Washington, DC, 2003.

National Research Council. Alerting America: effective risk communication : summary of a forum. National Academies Press: Washington DC, 2003.

Acknowledgments: NAKFI would like to acknowledge the late Eugene A. Rosa of Washington State University for his significant contributions to this area. Gene was university professor of sociology and the Edward R. Meyer Distinguished Professor of Natural Resource and Environmental Policy. Gene was a pioneer in research exploring the sociologic aspects of nuclear engagement and communication.

IDR TEAM MEMBERS—GROUP A

- Robert L. Brent, Thomas Jefferson University, duPont Hospital for Children
- Daniel G. Cole, University of Pittsburgh
- Graham P. Collins, Freelance editor/science writer

- Annie B. Kersting, Lawrence Livermore National Laboratory
- Li Liu, Rensselaer Polytechnic Institute
- Raymond J. Sedwick, University of Maryland
- Kelly Servick, *Science* Magazine

IDR TEAM SUMMARY—GROUP 4A

Kelly Servick, NAKFI Science Writing Scholar, Science *Magazine*

IDR Team 4A was asked to create an initiative to restore the public's trust in nuclear technology in the face of a gap between public perception and scientific reality.

Disasters such as the accident at the Chernobyl nuclear plant in Ukraine and, more recently, at Japan's Fukushima Daiichi plant, combined with the government's failure to clearly communicate risk, have perpetuated the aura of suspicion and dread around the terms "nuclear" and "radiation." Whether in the context of a medical treatment, an alternative to fossil fuel, or a new waste facility, these terms are highly charged, even in cases where the scientific community finds little or no human risk.

The breadth and complexity of such a misunderstanding makes the 3-year time line suggested in the IDR challenge seem prohibitively short. But the team decided, given the ambitious spirit of the conference, that these first 3 years should be devoted to laying the groundwork for a large organization—a "National Center of Nuclear and Radiation Communication"—devoted exclusively to informing the public about nuclear technology. With a full-time staff of diverse experts and a steady funding source, such an organization could continue to expand and evolve long after this 3-year "deadline."

Hallmarks of Success

Before any initiative took shape, the group looked to a few success stories—including Canada's progress in identifying 21 possible waste disposal sites under the supervision of an ethics committee, and the ongoing operation of the Waste Isolation Pilot Plant (WIPP) in Carlsbad, New Mexico—for guidance. As psychologist Paul Slovik explained in the preconference podcast tutorial, these successes likely hinge in part on the sense of participation and involvement from the public. From a psychological perspective, individuals are more willing to take on a well-defined risk if they feel they have a choice and stand to benefit from a nuclear application. Having that risk imposed from outside, as in the planned Yucca Mountain waste storage facility, provokes feelings of fear and helplessness, the group concluded.

But beyond these broad examples, group members had more personal experiences with effective risk communication that offered guiding principles: One member served on a committee to explain the risk of contamination to a community in Colorado during the cleanup and closure of the Rocky Flats nuclear weapons facility. She witnessed a shift in attitudes as the community became less adversarial and grew to trust the visiting scientists on the committee. Another member shared experiences with explaining the risks of radiation—including exposure from medical procedures such as computed tomography scans—to expectant parents. His advice sometimes even helped couples with decisions about whether to abort or carry a pregnancy.

In these examples, trust arose from dialogue and a personal relationship. The individuals facing a perceived nuclear risk interacted with a knowledgeable and receptive *human*, rather than a set of directions from an immutable and impersonal government body.

But the IDR Team recognized that retaining the cooperative, personal spirit of these conversations when scaling up the problem to a broader national dialogue on nuclear technology is a thorny problem. Two questions took shape early in the discussion: How can a large-scale initiative targeting diverse segments of the public build and maintain this sense of trust? And can individuals be motivated to participate in a dialogue even when the influence of nuclear technology is not as immediate as the threat of local contamination or the health of an unborn child?

Achieving Independence, Maintaining Support

Keeping in mind the value of trust-based, two-way communication, the group began to envision a centralized organization that might create nuclear dialogue on a national scale. Since the public often gets conflicting reports about the true risks of nuclear technology, an ideal initiative would create a beacon of clear information in a sea of sensationalist and alarmist voices.

Concerns about funding shaped the team's vision from the start: any broad effort will require substantial and steady financing, which group members acknowledged would likely come from the government. Yet public perception of the government—particularly on matters of nuclear risk—create a stumbling block. Group members who have experience with the Department of Energy's communication on nuclear issues described its approach as "sanitized": aimed at revealing as little as possible about its actions and intentions to avoid provoking opposition.

Regardless of whether the agency has revised its approach, the federal government is bound up with the public's general feeling of mistrust, and cannot be the official mouthpiece for a fresh public communication effort, the group decided. Their solution—a new national center that would be an independent third party, much like the National Academy of Sciences. Like the Academy, this center would work to establish itself as a trustworthy, nonpartisan source of public information. It would act as a liaison between public interests/concerns and both government and nuclear industry. Diverse experts, from nuclear and radiological scientists and physicians to social scientists and communications specialists, would serve as full-time staff.

This organization would also align itself with the recommendations of the Blue Ribbon Commission on America's Nuclear Future, formed by the Secretary of Energy to assess U.S. policy on managing waste products from nuclear fuel. The commission's 2012 report calls for an "independent federal corporation" in charge of responsible oversight of nuclear waste disposal decisions and communication. While this new center would not focus exclusively on waste disposal, its contribution to the Blue Ribbon Commission's goals might allow it to draw financial support from the Nuclear Waste Fund, which collects fees from utilities that own or operate nuclear facilities, and which has amassed roughly 25 billion dollars to date.

Missions for a National Center

The team thought that laying out a detailed plan of action for this center would require a more complete understanding of public attitudes and areas of mistrust. Given the limited time frame of the conference, it instead focused on detailing the center's mission and core principles, in a form that might be useful for pitching the idea to decision makers in government.

Intraorganizational culture

A defining feature of the center would be a spirit of civic engagement among its employees. Spokespeople for government and industry may see their primary responsibility as defending the goals and reputation of their institution, not serving the interests of a public that may have doubts about (or outright aversion to) those goals. However, members of this new center should see themselves as advocates for the public's interests, and would commit themselves to a fair and inclusive dialogue with citizens, based on sound science and ethical standards.

Fostering dialogue

Members also agreed that any productive dialogue would require a deeper understanding of public perceptions. Ongoing surveys should inform the center's actions from day 1: experts would develop ways to identify both conceptual areas of misunderstanding about nuclear science and geographical areas where mistrust is particularly high. (In the spirit of transparency, the organization would also share the results of these surveys with the public.) The center would then organize and sponsor town hall meetings that target these areas of mistrust and give the public a chance to voice concerns and questions.

A second, related task would be to foster mutual understanding between the public and nuclear industry. The center would encourage utilities (waste and weapons facilities, power plants, etc.) to interact with the surrounding communities, either in person or through ongoing surveys. The presumed outcome of such discussions would be a greater sense of inclusion in future decisions, including the siting and design of future power or waste facilities.

Broad and adaptive education

Finally, the group identified a host of outreach possibilities to educate different age groups. Based on a feeling that students lack a strong foundational understanding of the science behind nuclear technology, members suggested new ways to motivate students: For elementary and middle school groups, these could include dynamic video games or summer camps. At higher levels, students might take advantage of massive open online courses (MOOCs) to develop their own informed opinions. And a series of nuclear-themed TED talks might engage a wide range of interested adults.

While IDR Challenge 4 was focused on "the public," a rather vague way to refer to nonspecialists, Team 4A felt it is important to note that even leaders and decision makers who are well informed about the nuclear enterprise may lack the skill to communicate risk or respond in times of crisis. A final requirement for the National Center of Nuclear and Radiation Communication would be to design programs that equip educators, policy makers, and other key providers of information with strategies for sending a clear, early message to the public, before suspicions and misinformation can take root.

After laying out the features of their ideal organization, the team acknowledged the enormous challenges involved in making it a reality. The question of funding weighed heavily on the closing discussions; several members doubted it would be feasible to access the Nuclear Waste Fund. But the team agreed that the diverse expertise at the conference had produced a novel vision—one worth fleshing out and presenting to policy makers with the hope of inspiring more deliberate and effective communication.

IDR TEAM MEMBERS—GROUP B

- Shahzeen Z. Attari, Indiana University
- Ronald L. Boring, Idaho National Laboratory
- Lydia M. Contreras, University of Texas at Austin
- Carolyn Crist, University of Georgia
- Frederic H. Fahey, Society of Nuclear Medicine and Molecular Imaging
- Kathleen L. Purvis-Roberts, Pitzer College
- Aaron J. Simon, Lawrence Livermore National Laboratory
- Andrew S. Whittaker, University at Buffalo The State University of New York

IDR TEAM SUMMARY—GROUP 4B

Carolyn Crist, NAKFI Science Writing Scholar
University of Georgia

IDR Team 4B was asked to design and think about how to fund a 3-year public–private initiative to better understand and bridge the perception/reality gap between the public and nuclear experts about the risks of the nuclear enterprise and to restore the public trust in the use of nuclear technology.

As part of this, the team outlined the various components of the “nuclear enterprise”—energy, medicine, weapons, food irradiation, and more. Recognizing that the public likely thinks about bombs, Chernobyl, and Fukushima when the term "nuclear" is mentioned, the team noted the importance of discussing the actual risks and benefits of nuclear technology. The team also emphasized the need to understand the true risks associated with the nuclear enterprise in order to truthfully communicate them to lay audiences. By communicating the full breadth of nuclear use, experts may be able to help lay audiences understand that their personal risks related to nuclear radiation are limited compared to the benefits.

To understand how a public perception program might be implemented, the team discussed successful awareness campaigns for other socially contentious subjects, such as smoking cessation, bicycle helmets, texting while driving, flu vaccines, anti-bullying, and the BP public relations efforts after the Deepwater Horizon oil spill. The team also looked at the "rebranding" and "trust-building" ideas promoted by BP, clean coal, Earth Day, and childhood obesity campaigns.

To capture all of these possibilities in a broad sense, the team decided the initiative should stick to a traditional scientific path of implementing a social science experiment with a pilot program. The goal of the proposed 3-year initiative is to plan, execute, and evaluate one or more pilot programs in specific communities to understand how attitudes change. The long-term goal is to evaluate public understanding of nuclear power, energy, and medicine in the United States. This 3-year initiative is the first step.

The Pilot

The team would like to encourage more positive public perception and support of the nuclear enterprise by either or both:

- A targeted energy and nuclear technology module in K-12 education,
- An outreach initiative designed to spark engagement and public discourse, most likely through a public relations campaign.

This approach is based on the idea that people get their information through multiple channels. The two main channels discussed were formal education in schools and, as adults, information through traditional media, social media, and lifelong education. In the first channel, teachers provide information to students on a daily basis, but in the other, adults seek and locate information from a variety of sources.

As part of the pilot, the team would study attitudes in several communities before and after the education module or public relations campaign. The use of several different communities—such as a location with hospitals that use medical isotopes, a neighborhood near a nuclear power plant, and an area with little or no relation to nuclear technology—would address the need to examine the differences in perception and background knowledge. To evaluate the situation, the IDR Team would like to employ the mental model mapping technique, which is an explanation of someone's thought process about how something works in the real world. Used for analysis in the early stage of design thinking and strategic design planning, mental models give psychological representations of real, hypothetical, or imaginary situations.

The evaluation tool would include a literature review, which would investigate the effective strategies used in other countries, such as positive public perception of nuclear energy in France, and successful communication campaigns employed in other fields in the United States, such as smoking cessation and the mandatory use of bicycle helmets. As part of this, the team noted the importance of "rebranding" the image of nuclear technology to emphasize its benefits and clearly stating the true costs and risks associated with the technology. Following the literature review, the team would conduct lay and expert interviews about nuclear technology, education, and communications to create the pilot programs.

Education

The first part of the pilot program would target the K-12 age group. In an education module about overall energy options and their supply chains, students can learn in a broad sense where energy comes from and how it is used. This would include oil, gas, coal, nuclear power, wind, solar, and biomass. Several tangible suggestions came to mind, such as books, packaged lectures, or hands-on demonstration kits to help children make a personal connection with energy technology. To build on that personal connection, the team would also like to include field trips or tours of local energy facilities, not only nuclear, for students to observe the workers, technology, and mechanics involved in the energy field. This component also involves the education and training of teachers in order to incorporate this module into their curriculum, which might include stipends for them to attend a summer short course or conference at the university level. In addition, the team recommends a specific module that targets high school students, possibly called Nuclear Science and Medicine, to inform students about the various applications of nuclear technology in energy, medicine, and food safety. This course would help high school students, who are more able to think abstractly about processes and chemical interactions, to develop a full understanding of nuclear technologies.

Public outreach

The second part of the pilot program would seek to spark engagement and public discourse through various media messages. This could involve a public relations campaign, advertising, and training of nuclear experts to better discuss their technologies and relevance to the public. One aspect of the intervention is creating a better crisis communication plan to promote transparency and facilitate trust after nuclear accidents, such as those at Three Mile Island and Fukushima, which highly influenced public opinion.

Based on communications research, the team identified six "success" factors to be incorporated into any messaging—knowledge and data, endorsement, medium, community, emotion, and why and how. Most of all, storytelling is a key component of helping the public to see a situation through the eyes of a nuclear expert or advocate.

By emphasizing knowledge and data, the team would use science-based facts and numbers to empower the public to formulate its own opinion and make decisions. For instance, no one was injured during the Three Mile Island incident, which many members of the public do not realize. Part of the problem in the past, the team agreed, is the separation between nuclear experts and the public in terms of knowledge. By keeping the general audience at arm's length and building an air of authority, experts have talked down to lay people or withheld information. For example, during the Fukushima accident, officials did not release information quickly or with total transparency, which caused public distrust.

In addition, endorsements from "celebrities" and community play a key part in the messaging strategy. The idea is to use a well-recognized person or character who can present the message as a trustworthy third-party speaker. For instance, Bill Gates is a highly visible public figure in technology and philanthropy, and Homer Simpson is a well-known cartoon character who works at a nuclear plant. The idea is that Gates-like figures appeal to the current acceptance of "nerdy intellectualism" while Homer-like characters can use humor and sarcasm to turn around the images burned in our minds from the past in relation to nuclear technology. As part of this, building a community around nuclear technologies through social media or college campus activism is crucial to spreading the messages in a way that encourages authentic buy-in from public stakeholders.

Another aspect pulls in various media—books, YouTube videos, or even a Hollywood box office hit. Within the various media, the messages and stories can appeal to emotion, such as a child being successfully treated for a disease with nuclear medicine. The point is that all messages must explain benefits of nuclear technologies rather than only communicating risks in a way people can associate with their own lives. Most of all, messages should find a way to give the audience a "why and how," or a call to action, to move forward with their new knowledge or favorable understanding of nuclear technologies. Depending on the community in the pilot program, this could be safety information for those who live near a nuclear power plant or a detailed but easy-to-understand brochure for a mother considering nuclear diagnostic tools and imaging tests for her child.

Evaluating the Pilot

Following the 3-year pilot program, the team would carry out measurements, evaluation, iteration, and repetition of the initial survey to see whether education and ad campaigns create new mental models about perceptions of nuclear technology. To measure efficacy, the answer comes from the "difference in the differences," both before and after the campaign and among the different communities used in the experiment. The evaluation would assess changes in beliefs, knowledge, and attitudes among families and communities.

As part of the design and evaluation, the team would search for funding sources from various organizations in order to convince participants and others that the information campaign is based on balance, transparency, and objectivity. Thus, a neutral party should execute the pilot study. Once evaluation of the 3-year pilot program is complete, the team would hope to partner with other organizations to continue the research process and find new ways to promote positive public perception of the nuclear enterprise.

IDR TEAM MEMBERS—GROUP C

- Marissa Z. Bell, SUNY University at Buffalo
- Keith S. Bradley, Argonne National Laboratory
- Megan Garcia, William & Flora Hewlett Foundation

- David J. Harris, National Academy of Sciences
- Bojan Petrovic, Georgia Institute of Technology
- Nicholas St. Fleur, University of California, Santa Cruz
- Susan M. Stevens-Adams, Sandia National Laboratories
- Mark Sutton, Lawrence Livermore National Laboratory
- Bao H. Truong, TerraPower LLC

IDR TEAM SUMMARY—GROUP 4C

Nicholas St. Fleur, NAKFI Science Writing Scholar
University of California, Santa Cruz

IDR Team 4C was asked to design a 3-year plan for bridging the gap between public perception and nuclear experts on the risks of nuclear energy. First the team rephrased its challenge that supports a more inclusive objective to better reflect the broad nature of nuclear technology.

"How might we better understand and bridge the gap in perception between the public and nuclear experts on the nuclear enterprise."

With this newly phrased task at hand, the team devised a 3-year time line centered on four stages: information collection and analysis, identification of a pilot project, pilot project execution, and project analysis.

Mind the Gap

The team's plan of attack for this challenge centered on the idea of "Mind the Gap," a risk communication challenge that requires increasing understanding between the public and scientists who cannot take a one-sided approach to its challenge. The problem must be tackled from both ends of the perception gap. As such, the team devised a plan to address scientists and the public equally. This short phrase as it relates to nuclear science risk communication can be broken into three parts: be aware of the gap, beware the gap, and tend the gap.

Be aware of the gap

To achieve success in a risk communication campaign, scientists must understand that their opinion of the benefits of certain aspects of the nuclear enterprise may not be the same as or resonate with the public.

Beware the gap

As previously mentioned, one of the risks with a communication challenge that involves the public and scientists is in addressing only one side of the equation. The team stated that it must be careful to not only reach out to the public, but to also reach out to scientists.

Tend to the gap

The team decided its approach would provide an objective message to educate the public on the nuclear enterprise. The team wants to allow people to draw their own well-informed conclusions. In keeping with its goal of objectivity the team decided to not use words such as "risk" or "benefit" when discussing nuclear energy with the public because it considers both words to be inherently subjective.

Information Collection and Analysis

Statistics from national surveys disclose the percentages of the public's opinion for or against the nuclear enterprise. They do not reveal the reasoning behind those perceptions or the emotions that elicit such opinions.

For Team 4C, the best way to gain knowledge about public opinion is by examining what information already exists on the topic. The team's first plan of action would be to conduct a meta-study that analyzes all of the previous scientific literature on the public's perception on topics such as nuclear energy, nuclear waste, nuclear medicine, and related issues.

The team allocated 4 months to developing the meta-study. In addition to looking through the scientific literature, the team would also reach out to different populations across the United States to gain first-hand knowledge about people's perceptions on the nuclear enterprise and compare those reactions to the reactions obtained from the meta-study.

Also included in the information collection stage is an effort to collect data from scientists on their thoughts about the public perception of nuclear sciences.

Identification of a Pilot Project

Nuclear science is a multifaceted enterprise. It encompasses medicine and energy as well as waste and radiation. The team decided that the best way to tackle the problem as a whole would be to focus on individual aspects of the nuclear enterprise. The team would use the data they obtain from their meta-study to determine which aspects of the nuclear sciences the public perceives as most important.

The team will then take three or four of the ideas and develop them into pilot projects. Each pilot project will take place over the course of several months during the 3-year program.

Pilot Project Execution

The next part of Team 4C's plan is to implement two to three pilot projects. The group divided the projects into those aimed at the public and those aimed at scientists.

Project for the public's perception

The group thought of enlisting stakeholders and opinion leaders as a way of reaching the public. One member came up with the idea of identifying 2,000 people in America who hold some sort of influence over the public and then presenting what it considers an objective explanation of the nuclear enterprise. Another approach to the pilot project dabbled with the idea of enlisting a well-respected celebrity to act as an opinion leader.

This led the group to another idea: using storytelling to educate the public about nuclear energy. One team member said that when people don't understand a topic or are not trained in it, they let their emotions dictate their opinions. Stories elicit emotions. The group figured a compelling (and scientifically sound) story about the nuclear enterprise could elicit a public movement. This idea was a bit controversial because team members were unsure of how they could develop such a story about nuclear energy that didn't play off of people's fears.

Project for the scientists' perception

To help educate scientists the task force would develop a guide that amasses the information they gathered from polling the public. The team would promote their guide to scientists at universities and national labs. The team thought that a best-practices guide would be a successful pilot project for scientists looking to educate the public about their work, which would help scientists learn to better communicate to the public. Or it could be reformatted in a way that is more user-friendly for the everyday person, such as through social media or an educational website/video.

Project Analysis

The final step would be to analyze how effective the projects were at bridging the understanding between scientists and the public on nuclear energy through a new meta-study and surveys. The team would conduct a failure/success analysis according to defined metrics to determine which pilot project worked best. The most successful pilot projects would then be put forth as a case study for other organizations looking to increase public awareness of the nuclear enterprise as well as help scientists understand public opinion on their work. Funding for this project would come from a neutral not-for-profit organizations.

Conclusion

After rephrasing their problem the team agreed on an approach to bridging the gap between scientists and the public about the nuclear enterprise. The team used the central idea of "Mind the Gap" to first understand the perceptual differences between experts and the U.S. public on nuclear issues. Then the team created a 3-year time line centered on four stages of collecting information, identifying pilot projects, executing pilot projects, and analyzing results. By attacking the challenge as a two-sided problem the team outlined a plan for creating pilot projects for both the public and the scientists that will help bridge the communication gap on nuclear energy.

IDR Team Summary 5

Define the means to promote U.S. interests in the international nuclear power field in an era of diminishing U.S. and Western European influence.

CHALLENGE SUMMARY

There are over 430 nuclear power plants operating across the globe today in 31 countries. They provide approximately 13.5 percent of all the electricity generated in the world today (down from a peak of about 17 percent in the early 1990s). This initial introduction and ramp-up of nuclear power was driven largely by the U.S. domestic program—more than 100 of those plants are operating in the United States—and by the resulting follow-on of the Atoms for Peace program in which the United States proactively shared its technology with others. The Soviet Union and its satellites were the other significant players. It should also be noted that about 240 research reactors operate in 56 countries.

Later, of course, additional nations implemented significant nuclear power programs such as the French, British, Japanese, and others. But in the early days, U.S. influence was fundamental to non-Soviet nations. U.S. companies sold and built reactors around the globe. The U.S. government was the sole and then major supplier of enriched uranium for fresh reactor fuel in the free world. The United States signed agreements (known as 123 agreements because they flowed from section 123 of the Atomic Energy Act) that outlined promises by nations cooperating with the United States on civilian nuclear matters in return for U.S. assistance. Such provisions could include the promise not to pursue nuclear weapons, or to transfer, enrich, or reprocess U.S.-origin nuclear materials without advance U.S. consent. U.S. leadership in the creation and empowerment of the International Atomic Energy Agency (IAEA), the Non-Proliferation Treaty, the

Fissile Materials Cut-Off Treaty, and many other fundamental structures of the nuclear regime were intended to assure nuclear power that was safe, secure, and did not allow civilian programs to be used for nuclear weapons purposes.

Over the past 20+ years the United States has lost its early and almost virtual monopoly and major influence over the conduct of others, and U.S. influence will likely continue to diminish. The United States has not built a domestic reactor in more than 30 years (although we now see a small number of new plants being constructed). All but one of the major U.S. companies' reactor vendors have either gone out of business or been bought by foreign firms. Many other nations now offer full fuel cycle services, including power plants, enrichment and reprocessing services, and fresh fuel. Russia, South Korea, India, and particularly China have significant nuclear power plant programs; they account for the vast majority of new plants under development. They also have the intention to market their nuclear technology to others and, notably, the South Koreans recently won a competition with the French and Japanese to build four large units in the United Arab Emirates. The South Koreans are also pressuring the United States as part of a new 123 Agreement to allow them to reprocess their spent nuclear fuel. Many additional countries have announced an intent or at least an interest in obtaining nuclear power plants, and the implications are potentially severe. Will it be Asia who will shape this future as U.S. and Western European influence diminishes? Does it matter and, if so, what needs to be done?

The United States is still the most important player in helping to shape the international nuclear regime of the future; its R&D agenda in universities and national labs is outstanding, and its regulatory system is still considered the global standard. The U.S. commitment to safety, security, nonproliferation, waste management, and the environment are as strong as ever, but its standing is no longer assured and its influence over the conduct of others has lessened. Other nuclear-leading nations benefit from the close ties that exist between their government and private industry. The challenge for the United States is how to reassert and sustain leadership in shaping the new nuclear regime in ways that best serve U.S. interests and priorities while preserving the separate roles of the government, private industry, nongovernmental organizations (NGOs) and others that provide the strength and transparency of the U.S. system.

Key Questions

- What is the status and trajectory of U.S. influence on matters of key importance to the emerging nuclear regime? What does the United States care about and how can it best ensure that its interests are served? What role does the United States see for the international agencies, particularly the IAEA, and what should it do to ensure their effectiveness?
- How can the government, industry, and NGO community work together better to optimize U.S. interests?
- How should the United States determine the right balance of safety, nonproliferation, security, waste management, and the advancement of nuclear technologies? How does it pursue its top priorities?
- There are many considerations that must be taken into account in launching agreements between the United States and other countries on nuclear cooperation and in leading new international treaties and agreements. Some are political but there are also substantial technical issues. There will be serious consideration of changes in the currently used fuel cycles and this leads to safety and proliferation issues. Much of the technology is in the hands of industry and not under (U.S.) government control. What are the likely fuel cycles and fuel cycle issues bearing in mind these considerations? How can the United States best take advantage of its universities and national laboratories?
- What should be the U.S. position on transboundary movement of materials and wastes and how should it best be pursued? Should the United States champion multinational cooperation on the back end of the fuel cycle, including waste management and disposal? How?

Suggested Reading

Miller SE, Sagan SD, eds. On the global nuclear future, vol. 1. *Daedalus* Fall 2009; 138(4):1-171.

Miller SE, Sagan SD, eds. On the global nuclear future, vol. 2. *Daedalus* Winter 2010; 139(1):1-40.

Nikitin MB, Andrews A, Holt M. Managing the nuclear fuel cycle: policy implications of expanding global access to nuclear power. Congressional Research Service, October 2012.

Nikitin MB, Ker PK, Hildreth SA. Proliferation control regimes: background and status. Congressional Research Service, October 2012.

IDR TEAM MEMBERS

- Joonhong Ahn, University of California, Berkeley
- Robert J. Budnitz, Lawrence Berkeley National Laboratory
- Benjamin M. Chase, Idaho National Laboratory
- Mark B. Halper, CBS, The Guardian, Weinberg Foundation
- Kathryn A. Higley, Oregon State University
- Alexa C. Kurzius, New York University
- Mark T. Peters, Argonne National Laboratory
- Per F. Peterson, University of California, Berkeley
- Natalia V. Saraeva, Argonne National Laboratory
- Tanju Sofu, Argonne National Laboratory

IDR TEAM SUMMARY—GROUP 5

Alexa C. Kurzius, NAKFI Science Writing Scholar
New York University

IDR Team 5 was asked to define the means to promote U.S. interests in international nuclear power in an era of diminishing U.S. and Western European influence.

At present, a number of factors contribute to the changing landscape of nuclear power worldwide. Rising foreign interest in nuclear technology, competition from other energy markets, and limited construction of new plants in the United States threaten the U.S. role as the long-standing nuclear superpower. In addition, public perception of nuclear power technology following the Fukushima Daiichi accident in Japan and complex U.S. export regulations make promoting and expanding nuclear power increasingly difficult.

Drawing on the country's strengths, the team discussed the nuclear power enterprise in the United States and developed proposals that would help the United States maintain its position as a global leader. They dubbed their solution Nuclear 2.0, a group of ideas that embraces today's global political and market climate and possesses momentum for the future.

First, a little bit about U.S. nuclear power technology in an international context. This country has more nuclear power plants in operation than any other nation, with 99 currently in use. The new reactor designs of several American firms are considered among the best in class for their technology and passive safety features. Westinghouse's AP1000®—an advanced light-water reactor being built in the United States and China—is one of the best current examples of superior technology and passive safety. The development of its precursor was supported by funding from the Department of Energy in the 1990s.

The safety culture of the United States is, in a positive sense, unlike almost anywhere else. The team discussed how this emphasis on safety drives operational standards for nuclear power facilities and why the United States has a special culture of reporting and correcting problems. Much is owed to the overall excellence of the Nuclear Regulatory Commission (NRC), an organization that is generally respected around the world as the gold standard for nuclear power safety regulation. But global dynamics are changing, altering the power structure, safety standards, and nonproliferation interests worldwide. Developing countries, including China, India, and Brazil, are building or continuing to expand their nuclear power systems. Some of the major developed countries too are looking to build more nuclear power plants, because they produce fewer carbon emissions than fossil fuel and deliver consistent power to the grid in the way that solar and wind energy do not.

The recent deals that Turkey struck with Russia and Japan to build nuclear reactors are also examples of the changing global dynamic. The team agreed that these deals are significant practically and politically—in part because the United States was not part of the bidding process. In addition, Russia's decision to finance construction was discussed as one driven by geopolitical motivations.

The tenuous relations between the United Kingdom and China serve as an example of a developed country ostensibly ceding part of its nuclear enterprise independence to China, through the use of Chinese capital to build a new reactor in the United Kingdom. One team member speculated that it is a means to maintain nuclear capacity within the United Kingdom, despite the power shift.

Nuclear 2.0 is an attractive solution to maintaining U.S. influence because it relies on the country's very special ecosystem—an unparalleled scientific research base, strong university programs, national labs, capital markets, and a culture of innovation—as an environment that can promote nuclear power technology development for the good of the country, and for the world. This can also help maintain existing university programs in nuclear engineering, which are threatened due to a recent stagnancy in domestic research funding.

The team also recommended encouraging entrepreneurship and supporting existing startups in nuclear energy. As an example of how to spur innovation, a team member mentioned NASA's successful, modest investment in the commercialization of space. And given that venture capitalists are funding nuclear power companies around the country, the team agreed that funding small startups has potential to further develop the enterprise.

In terms of policy, the team recommended that a major positive development would be if the U.S. government promoted expanding U.S. export markets to allow the country to continue to be a global provider of nuclear reactors. They discussed the necessity for the country to support nuclear power technology advancement, through government funding, which is certainly as important as encouraging entrepreneurship. Financial incentives also came up as a way to support the domestic industry. And although this was not discussed at length, the nuclear waste challenge needs to be addressed, specifically high-level waste and spent nuclear fuel. The United States presently has no place to dispose of its nuclear waste permanently, which could complicate matters down the line, and already has.

The team also suggested strategic partnerships as a way to help secure a leading role for the United States in the future. One example mentioned was the Westinghouse-China agreement to build AP1000 reactors, among the safest and most economical Generation III+ reactors available. Also, investment from the oil and gas industries into the nuclear power field can help those companies remain relevant as the United States moves away from fossil fuel.

A more practical side of Nuclear 2.0 is the suggestion to change the cost model of nuclear power technology. One way to do this is to continue to develop smaller, modular reactors, which can be completely manufactured in one factory and installed onsite almost anywhere, including remote locations. Small modular reactors are developing technology that the team sees as having high potential; startup companies that manufacture these reactors came up in conversation as examples. Changing the cost model also includes the consideration of new revenue streams, such as using nuclear technology to produce heat, desalinate saltwater, and provide reliable power to the national grid.

With more countries expanding into nuclear power, global safety standards and nonproliferation have become a concern. U.S. policy was discussed at length, particularly the 123 Agreement. Authorized by Section 123 of the 1954 Atomic Energy Act, the 123 Agreement requires a specific agreement between the United States and another country as a condition for the transfer of nuclear energy-related technology for peaceful purposes.

The United States recently signed a 123 Agreement with Vietnam, opening up a potential market in that country. However, Vietnam also has deals with Russia and Japan, showing that the United States is not the only country with a stake in the game.

Overall, it is in the interest of the United States and by extension the world to follow through with our country's safety regulation systems as plants are being built globally. We have a proven track record for innovation and safety and countries, like Japan after Fukushima Daiichi, look to us for our expertise in putting in place methods for managing events both following incipient accidents and also during actual accidents.

Moreover, nuclear power technology offers an attractive future for clean energy, peaceful use of nuclear technology, the domestic economy, and the U.S. culture of science and innovation. Implementing the ideas included in Nuclear 2.0 can help protect the nuclear power industry in the United States and secure our position in the future.

IDR Team Summary 6

How might the widespread use of civilian nuclear power and associated fuel cycle facilities be made compatible with a world free of (or with a small number of) nuclear weapons?

CHALLENGE SUMMARY

In 2007, four distinguished American statesmen (George Schultz, Henry Kissinger, William Perry, and Sam Nunn) wrote of their support of "a world free of nuclear weapons." One year later, presidential candidate Barak Obama embraced this vision and, the year after that, President Obama expressed "America's commitment to seek the peace and security of a world without nuclear weapons."

Advocates of the abolition of nuclear weapons believe that it would make the world safer and more stable. Others argue that a nuclear-weapons-free world would be less secure and less stable than feasible alternatives (e.g., markedly reduced numbers of nuclear weapons, greater transparency, elimination of "hair-triggers," and enhanced security of nuclear materials). Still others believe that global zero is neither desirable nor achievable.

Among the perceived obstacles to achieving and maintaining a world with zero (or a very low number) of nuclear weapons is the substantial and growing civilian use of nuclear energy. Ensuring that materials from civilian nuclear facilities are not diverted to military use is a central feature of the Nuclear Non-Proliferation Treaty (NPT). Facilities for enriching uranium can be used to produce low-enriched uranium fuel for nuclear power reactors and/or to produce highly enriched uranium for weapons. Plutonium separated from used reactor fuel can be recycled to produce electricity or can be used to make weapons.

Substantial international growth of the use of nuclear energy surely would be accompanied by expansion of enrichment capacity, and probably also by expansion of plutonium production capacity. The spread of these dual-use capabilities would exacerbate the challenge to achieving and maintaining a nuclear-weapons-free world.

Key Questions

- How might the civilian nuclear enterprise be modified to minimize the risk of diversion of technology and materials to the production of nuclear weapons?
- How might the civilian nuclear enterprise be modified to maximize the time required to produce nuclear weapons using diverted technologies or materials?
- What technical and institutional measures might realistically be implemented to achieve acceptable levels of verification of nondiversion to weapons use?
- How might the NPT realistically be modified or complemented to achieve desired levels of transparency and stability?

Suggested Reading

Blechman BM, Bollfrass AK, eds. Elements of a nuclear disarmament treaty: unblocking the path to zero. The Stimson Center: Washington, DC, 2010: 57-116. (Pages 57-116 are available to conference participants. You will need your *Futures* Network username and password to access these chapters. Reprinted with permission from the Stimson Center.)

Nikitin MB, Kerr PK, Hildreth SA. Proliferation control regimes: background and status. Congressional Research Service Report RL31559, Oct. 25, 2012.

Because of the popularity of this topic, two groups explored this subject. Please be sure to review the other write-up, which immediately follows this one.

IDR TEAM MEMBERS—GROUP A

- Rodney M. Adams, *Atomic Insights*
- Carol J. Burns, Los Alamos National Laboratory
- Raymond P. Mariella, Lawrence Livermore National Laboratory
- Charles McCombie, Arius Association
- Catherine H. Middlecamp, University of Wisconsin–Madison
- Jessica M. Orwig, Texas A&M University

- Francis Slakey, Georgetown University
- Kumar Sridharan, University of Wisconsin–Madison,
- Paul P.H. Wilson, University of Wisconsin–Madison

IDR TEAM SUMMARY—GROUP 6A

Jessica Orwig, NAKFI Science Writing Scholar
Texas A&M University

IDR Team 6A was asked to address how the widespread use of civilian nuclear power might be made compatible with a world that has few or no nuclear weapons.

The challenge is an issue dating back to 1946. Less than 1 year after the end of World War II, the United States wrote the Acheson-Lilienthal Report—the first document to recognize the need to control and limit the proliferation of nuclear weapons to reduce the risk of nuclear war.

A Stark Reality

Fast forward 67 years, and the nuclear-weapons-free world that the Acheson-Lilienthal Report envisioned is a fading dream. Nine countries have acquired nuclear weapons technology and built and tested their products, several of which did so either partially or completely in secret. More than 2,000 nuclear test explosions have taken place around the world. And countries maintain stockpiles that number in the hundreds to thousands.

This stark reality is due in part because as weapons programs develop around the world, nuclear fuel cycle technology continues to spread. Nuclear power provides a cost-effective, low-carbon form of electricity compared with many fossil fuels, and is therefore a leading weapon in the battle against rising levels of carbon dioxide in the atmosphere. Herein lies the complication: the same technology that can produce low-enriched uranium (LEU) for nuclear power, a burgeoning source of clean, alternative energy, can also create weapons-grade, highly enriched uranium.

The United Nations founded the International Atomic Energy Agency (IAEA) in 1957; this agency oversees and regulates civilian trade activity of uranium and plutonium worldwide. Despite the IAEA's efforts to limit the proliferation of nuclear weapons by enforcing and upholding safeguards set by the Non-proliferation Treaty (NPT), breakout remains an ever-present threat.

With nearly seven decades of tension dividing peaceful applications and military applications of nuclear materials and technology, the team concluded that they needed a novel approach if they were going to present a solution that could, in theory, work. Ultimately, they proposed a contemporary twist on an existing idea that has, for political and economic reasons, never been tried: establish a capitalistic-driven nuclear market, composed of regional or multinational-owned alliances that market nuclear energy at competitive prices. The team approached all aspects of the business including such issues as fuel management and shared liability in the event of an accident.

Capitalize on a Nuclear Market

Thirty-one countries use nuclear power as either a primary or secondary energy source. At least nine of these countries produce the LEU necessary to power their reactors while others purchase the material. The team's overall consensus was that the threat of military proliferation with help from state-owned fuel cycle facilities is a political nightmare. So, at its heart, their solution was to reduce the number of state-owned fuel-cycle facilities capable of enriching uranium and reprocessing plutonium in favor of a "global service model."

The way to do this, team members suggested, is to create a competitive international market for nuclear fuel. Imagine a world where different regional or multilateral alliances, located across the globe, supplied nuclear material. To be competitive with each other and capable of supplanting current, state-owned fuel-cycle facilities, each entity would offer a series of commodities and services, for example, reactor technology, fuel supply, shared liability and assets with the buying country, and agreements to take back spent fuel and dispose of the nuclear waste. Instead of today's Nuclear Suppliers Group (NSG), a multinational body that controls certain trade and transfer of nuclear material, the new model might include multiple "Nuclear Buyers Groups" that manage regional energy commerce. The idea being that these alliances could become competitive enough to make state-owned fuel cycle facilities obsolete, while also providing diversity in a sociopolitical context to facilitate interactions with all countries, including non-weapons states. In turn, this would reduce the number of states with facilities that could be adapted for weapons capability, while enabling safe, transparent application of nuclear power.

Facilities that control the global supply of nuclear material were first suggested in the Acheson-Lilienthal Report 67 years ago, and later in multilateral agreement proposals in the NPT. Specifically, the Acheson-Lilienthal Report proposed an "Atomic Development Authority" which would have been a single international agency that controlled the world's supply of nuclear material and would release small amounts at a time to individual states. The difference in the team's approach is that they put a capitalistic spin on an otherwise seemingly monopolistic scenario. Key to their solution is the involvement of politically diverse stakeholders.

Technology with Transparency

What will mitigate the risk of further proliferation and/or diversion of materials? After all, profit drives capitalistic markets, and nuclear weapons-grade uranium could prove more lucrative than LEU, especially in the absence of individually, state-owned nuclear weapons technology. To limit this possibility, the team proposed that the international nonproliferation regime and the role of the IAEA must be strengthened. This includes both real commitments to the reduction of existing stockpiles and adoption of business models with best practices, such as those promoted by the NSG, the IAEA, and the World Institute for Nuclear Security. The team argues that these practices should include a strict code of ethics to which alliances would adhere, and terms regarding safety, security, longer-term waste disposal models, and last but not least, transparency.

Transparency is perhaps the most challenging of the terms, but advanced technology could help. For example, technology with built-in systems that automatically monitor and record operation, status, and security could increase confidence in the security of energy systems. Additional benefits could come from alternative fuels and novel detection technologies that could readily identify any covert activity concerning processing of highly enriched uranium.

Transparency ties to another important facet—trust: trust between consumers and suppliers, between competing companies and—in this case—between nation states. Suppose every nuclear weapon, save one, vanished overnight, and the only one left was under North Korea's control. The political mistrust between North Korea and other states like the United States, China, and Russia would almost certainly spark a frenzy of nuclear weapon production the following morning by those and other states. Trust and the lack thereof are, in part, why states with nuclear weapons are unwilling to relinquish or even reduce their supply and also a partial reason behind a growing desire for nuclear weapons by non-nuclear weapons states.

Cultivate a New Culture

Nuclear weapons provide a certain level of political power and are therefore a desirable commodity. The underlying culture of power, political gain, and persuasive advantage that come with the possession of nuclear weapons must change if a world with widespread civilian nuclear power and little to no nuclear weapons is to ever exist, the team argued.

If at all possible, transform the cultural attitude surrounding the possession of nuclear weapons from positive to negative, one team member argued. Right now the proliferation of nuclear weapons has more of a negative aura, hence extensive clandestine efforts by certain states to obtain nuclear weapons designs and technology. Extrapolate that attitude toward the possession of weapons, and it might further discourage non-nuclear weapons states' desire for nuclear weapons and possibly motivate a reduction in nuclear warhead stockpiles by nuclear weapons states.

Another approach to discouraging non-nuclear weapons states' self-asserted need for independent state-owned fuel cycle capabilities would be sharing liability and control of nuclear material across multiple nations. The competitive, multinational fuel-cycle facilities the team proposed would be owned by both nuclear-weapons and non-nuclear weapons states. From such a collaborative effort, the strong political divide separating the two states might be softened.

What Waits to Be Seen

If the team's model began to take root tomorrow, it could not fully mature as described. A major hurdle that the companies would face, and which governments are facing today, is long-term disposal of nuclear waste. Moreover, the likelihood that civilian nuclear power will continue to expand means more waste and an even greater need for a solution to long-term nuclear waste disposal. Furthermore, the advanced technologies that could readily promote transparency remain to be developed. Nuclear scientists and engineers can measure the residual signatures of a nuclear test, but they have yet to design an instrument capable of verifying that material is not associated with a military program without revealing sensitive national security information.

Finally, the team discovered that in order to answer one question, they had to ask each other a myriad of other questions. Perhaps the most relevant was, "What's different about 2013 that might make our model possible when a similar model did not work 50 years ago?" One outstanding difference is the impending need to reduce the levels of carbon dioxide and other greenhouse gases in the atmosphere. Another is that compared to times during the Cold War, when nuclear proliferation seemed politically necessary, proliferation is now openly portrayed as an undesirable act. For example, in 2010 the United States and Russia signed the New START Treaty, which commits the countries to reduce their number of nuclear weapons. Furthermore, in June 2013, U.S. President Obama announced new plans for reducing both U.S. and global nuclear weapons stockpiles. With changing climates and changing attitudes, there might be room for great changes in nuclear policy, too. Will we soon as a nation be deciding the origin of our nuclear fuel by casting votes on ballets etched with company names like "Nuclear Now" or "Clean, Green Nuclear Machine"? That waits to be seen.

IDR TEAM MEMBERS—GROUP B

- Matthew T. Domonkos, Air Force Research Laboratory
- Audeen W. Fentiman, Purdue University
- Elisabeth A. Gilmore, University of Maryland
- Seth A. Hoedl, Harvard Law School
- Jyoti Madhusoodanan, University of California, Santa Cruz
- Mark W. Maier, The Aerospace Corporation
- Robert Rosner, The University of Chicago
- Alexander H. Slocum, Massachusetts Institute of Technology

IDR TEAM SUMMARY—GROUP 6B

Jyoti Madhusoodanan, NAKFI Science Writing Scholar
University of California, Santa Cruz

IDR Team 6B was asked to identify ways the widespread use of civilian nuclear power might be made compatible with a world free of, or with a small number of, nuclear weapons.

The team agreed at the outset that the present challenge was not framed accurately. Concerns with expanding civilian nuclear power have focused on their potential to be diverted and exploited for weapons development. But civilian uses of nuclear energy are not the primary bottleneck preventing a "Global Zero" nonproliferation treaty that aims to reduce the number of weapons worldwide to very few, or zero. Instead, governments' reluctance to enter such agreements stems, in no small measure, from their disagreement with enforcement policies.

The team agreed that expanding civilian nuclear power across the world has many advantages. According to them, nuclear power is the most practical technology currently available to reduce CO_2 emissions from fossil fuel use quickly. Expanding nuclear power facilities will also support the economic growth of all nations, and concurrent increases in their energy needs. With this background, Team 6B reframed the challenge question: How can we create a framework that facilitates civilian nuclear power without undermining a "Global Zero Treaty" in the future?

The team recognized that all potential solutions have both technical and political aspects. Policy-based solutions rely on technological safeguards, but technical safeguards only work within a political framework. They attempted to achieve one goal with their recommendations, namely: What interventions can we propose today that will remain relevant in 30 years? Toward this broad objective, the team focused on three questions:

- What technologies, if promoted, have the potential to minimize the misuse of nuclear technology?
- How might technical and political interventions internationalize the nuclear fuel cycle?
- How can we promote the development of improved detection technologies?

Technologies to Minimize Misuse of Nuclear Technology

Enriched uranium is the most commonly used nuclear fuel in light-water reactors today; spent fuel from such reactors contains plutonium, another fuel obtained by reprocessing this material. Both materials are easily diverted or exploited for use in weapons rather than power production. The worldwide spread of light-water reactors means a global infrastructure of uranium enrichment—creating a source of fuel for nuclear weapons.

Hence, Team 6B recommended reducing global dependence on light-water reactor technology that uses these fuels. Stockpiles of uranium and plutonium in enrichment facilities and waste repositories also create vulnerable targets that may be attacked even with nonnuclear weapons. Thus, the team suggested increasing the use of alternative fuel technologies that can potentially decrease these vulnerabilities, and thus reduce concerns of weapons proliferation. As an example, they discussed technologies that use thorium. Unlike uranium, thorium does not need to be enriched before use. The spent fuel from a thorium-based fuel cycle is too contaminated to be easily reused in weapons, and is more easily traceable.

Safer, proliferation-resistant reactor designs and fuel cycles

IDR Team 6B began by identifying what makes one fuel cycle superior to another with respect to facilitating widespread nuclear power, but few or no nuclear weapons. Factors such as cost, ease of production, and compatibility with global deployment were considered most crucial, since a fuel cycle that failed to meet these criteria would be unsuitable for widespread power production. Safe, secure reactor designs that meet these criteria would lower barriers to adoption of the new technology and help enforce tracking of resources. The team also agreed the technology should be intrinsically resistant to clandestine diversion or exploitation. Thus, there should be no weapons-suitable materials involved, and the steps involved in the fuel cycle should not be easily diverted or exploited for use in weapons, as they are in the current light-water cycle.

Having defined this “ideal” nuclear fuel cycle in concept, the team analyzed the fuel-once reactor, a developing technology that meets many of these criteria. One caveat the team recognized is that current fuel-once reactors still use highly enriched uranium, which is directly usable in weapons. However, the reactor minimizes other infrastructure and processes that have historically been vulnerable to proliferation exploitation.

They discussed the steps needed to promote the widespread use of this ideal reactor, both nationally and globally. Team 6B thinks giving the Nuclear Regulatory Commission (NRC) the budget and authority required to license this reactor would catalyze interest from private investors and startup companies. The team also suggested that the Department of Energy support the deployment of at least two pilot systems based on the fuel-once reactor technology to meet non-carbon energy targets. Data gathered from these pilot systems could then inform the NRC licensing decision.

Global Inclusivity

IDR Team 6B recommended adopting a more inclusive international stance to “level the playing field,” so all countries have access to nuclear power technology. Two political aspects to achieving this goal are to create an expanded nuclear energy supply to meet global needs, and ensuring appropriate global perspectives of those who enforce international nuclear policies.

At present, state-of-the-art reactor technologies are held proprietary by specific U.S.-based companies, so even if other countries have fuel resources, they cannot necessarily use them in the best way possible. Potential technical solutions to this problem may be to standardize some aspects of fuel cycle technologies across the world, perhaps by creating an international center that everyone can access.

Another technical solution would be to internationalize repositories for intermediate and permanent waste storage. In this scenario, each country would run its own reactors, using common international fuel sources and repositories. When fuel rods needed replacement, they would be transported to a repository where they would be secured in part by using technical means such as to safely store or dispose of fuel pellets. This approach requires standardization of fuel cycles and assemblies among nuclear power–generating nations.

Team members also emphasized the need for an improved nonproliferation treaty. Current regulations do not restrict access to nuclear resources when nations break the treaty. As a result, a country that signs the non-proliferation treaty, acquires enriched uranium, and then breaches the agreement does not lose access to these resources. Despite their noncooperation, such a country can then use civilian nuclear resources to develop weapons.

Improving Detection Technologies

IDR Team 6B proposed improving available technologies to track fuel cycle resources so they are less easily diverted or exploited. Their suggestions on how to achieve this goal focused on policy-based interventions. They emphasized the impact of governmental choices early in the planning process, drawing a parallel to the development of GPS technology.

Navigation systems are now familiar to anyone trying to reach a grocery store in a new city. But GPS technologies were originally created for, and restricted to, military applications such as guiding weapons. However, policy makers at the time specifically chose to develop the technology with signals that could eventually be deployed differently for both civilian and military uses. As one group member noted, this decades-old, conscious decision enabled civilian applications of a potentially high-risk technology originally developed for military applications.

Team 6B suggested implementing a Grand Challenge to develop an open-access monitoring system for fuel cycle resources. Grand Challenges, a recent government initiative, offer incentives to companies and researchers who identify innovative solutions to important national or global problems. Deliberately seeding crowd-sourced applications could accelerate progress toward a viable solution. However, the team also recognized that crowd-sourced solutions, which may be highly reliable for detecting true violations, often carry the caveat of frequent false alarms.

Next Steps

IDR Team 6B recognized that establishing a "Global Zero Treaty" does not hinge upon civilian applications of the nuclear fuel cycle. A significant shift in international treaties may be the only way to reduce or prevent overt diversion of physical resources or exploitation of fuel cycle knowledge to military applications. Clandestine operations, however, may be reduced with technologies that are inherently more resistant to diversion, and improving detection techniques to monitor global activity.

Team 6B identified specific technological and political steps to decouple advances in civilian nuclear fuel cycle applications from global nonproliferation agreements. One suggestion was a Grand Challenge to develop an open-access monitoring system for nuclear fuel cycle resources. The team also recommended specific policy changes to support the development of safer, tamper-resistant and proliferation-resistant reactor technologies, such as small modular reactors and fuel-once reactors. Both technologies—improved reactors and better detection systems—have the potential to scale internationally to meet energy needs, reduce carbon emissions, and promote economic growth.

IDR Team Summary 7

Identify a new and practical application of nuclear phenomena for the benefit of humankind.

CHALLENGE SUMMARY

Although nuclear phenomena have been understood only over the course of the last century or so, the applications of nuclear technology have been widespread. They include the following:

Medical diagnosis and therapy
Energy production for electricity generation, district heating, process heat, propulsion systems, and desalinization
Sterilizing medical equipment
Scientific research ranging from tracers to sample dating
Preserving food
Propulsion and station energy for spacecraft
Controlling insect infestations
Nondestructive testing and examination
Weapons

These applications are diverse, but most of them were developed many decades ago. Although there have been both incremental and significant advances, the fundamental applications of nuclear technology have not expanded to new spheres.

Over this same period there have been great advances in the application of science. For example, in recent decades there have been extraordinary advances in the application of materials sciences, including the development of nanomaterials, materials with greatly enhanced properties, novel fabrication techniques, and more. At the same time, bioengineering has emerged as a powerful vehicle for many advances in medicine, food, and energy production. Computational capacities have expanded greatly in ways that enable the understanding, design, fabrication, and control of systems in ways that were not previously conceivably.

Given that great advances in one technology often arise from the application of advances in others, the question arises: Are there practical applications of nuclear phenomena for the benefit of humankind that are now feasible, but that have not been previously exploited or perhaps even been contemplated? The focus here is less on exploring potential future applications that already have had established programs (e.g., fusion, fast reactors, transmutation of waste) than on identifying new, innovative applications that may now become practical due to advances in enabling technologies.

Key Questions

- Is there a practical application of nuclear phenomena for the benefit of humankind that has not previously been exploited?
- What advances, if any, are necessary in order to enable that application? What advantages for the achievement of the function does nuclear technology provide over other alternatives? What risks?
- How can we galvanize research and development to explore and exploit these promising applications?
- How can we attract and retain the best of the coming generation to address these opportunities?

Suggested Reading

Constable G, Somerville B. A century of innovation: twenty engineering achievements that transformed our lives. Joseph Henry Press: Washington, DC, 2003.

Because of the popularity of this topic, two groups explored this subject. Please be sure to review the other write-up, which immediately follows this one.

IDR TEAM MEMBERS—GROUP A

- Jesse H. Ausubel, The Rockefeller University
- Joshua E. Daw, Idaho National Laboratory
- Rachel Feltman, New York University
- John F. Holzrichter, Lawrence Livermore National Laboratory; Hertz Foundation (retired consultant)
- Jae W. Kwon, University of Missouri–Columbia
- Samuel S. Mao, University of California, Berkeley
- Beth-Anne Schuelke-Leech, The Ohio State University
- Mercedes V. Talley, W. M. Keck Foundation
- Jianzhong Wu, University of California, Riverside

IDR TEAM SUMMARY—GROUP 7A

Rachel Feltman, NAKFI Science Writing Scholar
New York University

IDR Team 7A was asked to identify a new and practical application of nuclear phenomena for the benefit of humankind. Despite a lingering fear of the technology, nuclear science has many applications that contribute to humanity's health and comfort. But with the study of nuclear physics no more than about a century old, it can only be assumed that the greatest applications are yet to come. Some of these new applications could be just around the corner, but the vast majority are still far off from the early stages of development.

While taking a "pie in the sky" view of the problem—that is, brainstorming on problems that humanity needs to solve, and then working backward to find some way of assigning theoretical nuclear solutions to them—Team 7A focused on industries that already use nuclear technology and hypothesized on new and different applications of the science. By systematically reviewing dozens of nuclear devices already used or currently in development, the team was able to connect early research in these fields to possible future industrial application.

Are We Stuck?

Nuclear technology, the team posited, was a premature discovery. The theoretical advancements of nuclear technology in the 1920s and 1930s were "normal," but World War II caused a push into weapons at an unnatural rate. After a burst of technology over the course of 5 years or so, the team agreed, it took several decades for any more progress to be made. What does this mean for innovation? When fascination with nuclear technology was high, our understanding of it was actually quite low. As a result, many potential applications of nuclear technology—like Project Pluto, which aimed to design a nuclear-powered ramjet engine in the 1960s—were proposed and thrown out before anyone had the means to produce them practically. And other applications in that era were too "exuberant," like the Russian program called Nuclear Explosions for National Economy, which detonated over 100 nuclear devices to clear mountains in the way of interstate highways and loosen natural gas for extraction. After a few postwar decades of similar nuclear applications, the team felt, the world had responded with a backlash of fear and sobriety, especially as the medical and environmental implications of nuclear waste were fully understood. Now, the team agreed, with that sobriety still in mind, we need to break out from the tired perception that nuclear technology is primarily suited for making weapons, and for making the same old kind of power plant.

What Can Nuclear Materials Do?

With giant post-it notes at the ready, the team undertook the Herculean task of outlining the entire nuclear industry point-by-point. Failing an invention appearing on the conference room's table, they agreed, it was better to take some old ideas and reinvigorate them. First, the group discussed the properties that make applications of nuclear particles so valuable: most obviously, nuclear reactions contain lots of energy. This lends it to applications in the energy sector as well as for use as a weapon. Additionally, radiation rays and particles are remarkably good for signaling, both in the human body and in exploring beneath the surface of the Earth. Intrinsically, nuclear materials are a source of very high temperatures as well.

Current Applications

These properties have made nuclear materials valuable in several areas of industry, which the team outlined in part:

- Heat generation.
- Power plants.

- Tracing and imaging in medicine, especially for the diagnosis of cancer and other diseases, as well as some applications in treatment.
- Imaging below the surface of the Earth.
- Structure measurement.
- Deliberate mutagenesis, the microbiological technique by which DNA mutations are induced by exposure to radiation, allowing scientists to observe unique properties of mutant proteins, genes, strains of bacteria, and so on. Mutagenesis is also used by cancer researchers to understand the mechanistic pathways of the disease by observing the mutation of specific genes.
- Transmutation or the conversion of one element or isotope into another. This particular application actually makes our harnessing of nuclear energy less dangerous: radioactive waste, actinide elements such as the isotopes of plutonium, can be irradiated and made to undergo nuclear fission. The waste loses these original isotopes, replaced with fission products that have shorter half-lives and will therefore degrade to nonradioactive elements much more quickly.
- Semiconductor doping, where impurities are deliberately introduced into an intrinsic, or very pure, semiconductor. This process allows for the modification of the semiconductor's electrical properties.
- Explosive devices, which can be applied as bombs in the military sector as well as for construction or mining purposes.
- Nuclear batteries.
- Food preservation through irradiation.

New Ideas

By discussing current research in all of these fields, the group came to focus on several possible future applications.

Waste disposal, mantle exploration

First, the team discussed an old idea with a new application. It's been theorized that an old proposed method of disposing of nuclear waste—that is, putting waste inside a titanium shell, drilling a borehole, and taking advantage of the waste's heat and weight to make it drop into the earth—might also allow us to create images of the deep crust of the upper mantle. These payloads could reach the mantle in a year or so, providing the perfect opportunity to collect data.

Hydrogen production

Another old idea was presented with promising new research to support it. The production of hydrogen as fuel from nuclear heat has long been a goal, which is why people want high-temperature reactors. Hydrogen is the dream of the sustainable energy sector, but you'd need to produce a lot of it to replace conventional fuel. It's feasible, but you need those high temperatures. Recent research, which was presented at the American Geophysical Union meeting in December, showed that using aluminum as a catalyst can initiate a hydrogen-producing reaction at 200 degrees Celsius. At that threshold, the present generation of reactors could produce lots of hydrogen.

The team also suggested that big data analysis could be used to find even more catalysts that allow for high rates of hydrogen production at current nuclear reactor temperatures.

Nuclear batteries

One team member drew a graph demonstrating the current distribution of nuclear energy supplies and their power. It showed that in the future, we could move from having tens of large GW power plants to billions of tiny nW batteries.

The group further discussed the feasibility of a smaller, more efficient nuclear battery, where radioactive particles interact with semiconductors—essentially producing electricity in the same way that solar panels do. Countless nuclear batteries are expected in the future in numerous applications and the group discussed production of nuclear batteries.

This, along with the following discussion of combined heat and power (CHP), led to an interesting revelation: that the next step of nuclear technology must lie in the small- and mid-range of energy production.

Combined heat and power

One team member suggested an elaborate way of combining heat and power. CHP plants already exist, but a novel design could make them more resilient and universally useful. Instead of boiling water to drive the turbine of the power generator, similarly to nuclear batteries, CHP might employ solid-state generators with no moving parts, and while it would be smaller and have less output than current modular reactors, the lack of moving parts would make it more suited for use in developing countries and remote areas, as less maintenance and supervision would be necessary.

A team member described a concept called "arctic sun." He pointed out that progress in high-temperature materials and in efficient, low-cost solar cells might make possible a means to remove energy from a nuclear powered source via the radiated optical and infrared power. The topic began in 1963 with primitive photocells and has been used from time to time in low-power, low-efficiency space power supplies. However, with modern fission reactor materials, allowing reactors to reach temperatures of 1,400 to 1,500 degrees C, and employing modern solar cells reaching 35 percent or more, this technology is ready for reexamination as a solution for mid-level power applications, such as efficient, very reliable 0.1- to 3-MW power sources.

Conclusions

The industry, the team concluded with great help from the graph in the final presentation of their discussion, has been obsessed with one model for a while—large-scale nuclear reactors—trying to produce the Cadillac over and over again. But the group drew a chart that plotted the energy production of large-scale nuclear reactors, showing how massive the difference truly is between those methods and other fuels, such as coal and solar energy. Why not aim for the middle? And on a smaller scale, the team agreed, mistakes would be much smaller too—if something went wrong, the situation would be infinitely more containable than from a large reactor. These four new applications—nuclear batteries, hydrogen production, imaging and exploration of the Earth's mantle, and solid-state CHP reactors—represent areas of the nuclear technology sector that are ready and able to grow. These are old ideas, yes, but with the potential to finally be used in new ways.

IDR TEAM MEMBERS—GROUP B

- Yousry Y. Azmy, North Carolina State University
- William A. Garner, International Atomic Energy Agency
- Kate Horowitz, Johns Hopkins University
- William H. Newell, Association for Interdisciplinary Studies
- Neal Stewart, University of Tennessee
- Pallavi Tiwari, Case Western Reserve University

- Chadwick L. Wright, The Ohio State University Wexner Medical Center

IDR TEAM SUMMARY—GROUP 7B

Kate Horowitz, NAKFI Science Writing Scholar
Johns Hopkins University

IDR Team 7B was asked to look both outside of the box and beyond the wealth of existing technologies to envision an entirely novel and meaningful use of nuclear phenomena for the benefit of humankind. Undaunted by its ambitious assignment, the IDR Team rallied to emerge from this year's National Academies Keck *Futures Initiative* (NAKFI) conference with a number of impressive and practical innovations.

Current applications of nuclear phenomena include generating power, medical diagnosis and therapy, sterilizing medical equipment, agricultural pest control, preserving food, and many others. To begin moving beyond what has already been done, the IDR Team employed a two-pronged approach, looking first at nuclear science's capabilities (What can it do?), and then examining existing global issues for possible solutions (What do we need it to do?).

What Can Nuclear Phenomena Do?

One of Team 7B's first orders of business was to create a list of properties or "special features" unique to nuclear objects and phenomena. As outlined by one IDR Team member, nuclear reactions have an extraordinarily high energy density, are small and fast, occur in very large numbers, can penetrate materials at various depths, can be used to identify materials through passive or active interrogation, and can affect targets microscopically at a local level. The list informed Team 7B's explorations and has the potential to frame nuclear innovation for years to come.

What Do We Need It to Do?

With these powerful tools in hand, the IDR Team turned to contemplate a planet in crisis. Areas of humanitarian interest included climate change, the effects of overpopulation, food safety, and water shortages, all of which determine both public health and quality of life for Earth's 7 billion inhabitants. During the course of the conference the team considered a multitude of suggestions, from the practical to the impossible, but two concepts gained special traction. Both ideas have applications for agriculture in the United States and the world, and—more crucially—both ideas offer nuclear solutions for multiple major problems.

Bug zapper

Water is one of the few things essential for human survival, and yet the confluence of human expansion across the globe with catastrophic climate change is driving a water shortage that will prove devastating in the near future. Fresh, potable water is a nonrenewable resource that must be conserved for direct human and animal consumption. Unfortunately, nonpotable water (in the form of lakes, streams, groundwater, and gray water) is riddled with pathogens and therefore unsafe for irrigation and other uses, which means that many large farms are irrigated with precious drinking water.

The alternative is no better. The number 1 source of foodborne pathogens on fruits and vegetables is irrigation water. Bacteria and viruses such as *Escherichia coli, Salmonella, Listeria,* and *Staphylococcus aureus* are inadvertently sprayed onto crops in irrigation water and find their way into human bodies, where they can become deadly.

To combat both sides of the problem, the IDR Team proposed irradiating nonpotable water to sterilize it and eliminate the risks of covering food crops with pathogens. Using nonpotable water, a previously dangerous source, eliminates the need for farmers to drawdown the local supply of fresh drinking water, and "zapping the bugs" or microbes ensures that their crops will remain safe for human consumption.

Hot garbage

The IDR Team's second big idea makes unlikely use of existing nuclear technology: the power plant, or, more specifically, its by-products. Nuclear fission generates an enormous amount of excess heat, which power plants channel into nearby bodies of water. Team 7B conceived of capturing this heat and using it to accelerate the breakdown of organic matter, commonly known as compost.

Food and other organic materials comprise an enormous portion of the waste sent to landfills and incinerators each year. In 2011 alone, the United

States generated more than 36 million tons of food waste, most of which is currently occupying space in garbage dumps. As global population expands, so do our trash piles, but Earth cannot support or sustain the current rate of human waste production and disposal.

To address this issue, the IDR Team suggested constructing municipal composting areas near nuclear power plants. The compost sites could be added to any of the 99 active light-water reactor plants in the United States, or easily added to the blueprint of the plants currently under construction. The compost piles would sit atop slabs of concrete, into which power plants could release their excess heat, which would, in turn, provide a constant and hospitable environment for the bacteria that help break down organic matter. The process would allow cities to dispose of food waste and cut down on landfill bulk. In addition, the newly decomposed organic matter could be sold or otherwise distributed to local farms as a natural soil amendment.

Greener, cheaper, safer

The team considered many other ideas, all of which were focused on creating technology that is environmentally friendly and cost-effective and improves human safety, or all three. Team members discussed the possibility of mobile irradiation. A small, portable irradiator could bring immediate relief to disaster areas or developing countries in need of drinking water and sterilized medical equipment and blood for transfusions.

Botanical suggestions included using nuclear radiation to break down the tough celluloid wall of plants such as *Panicum virgatum* (switchgrass) for easier, more cost-effective biofuel production; mutating certain plants to improve their natural carbon absorption capacity; and developing plants as a renewable and relatively portable extractors for dangerous nuclear contamination.

One IDR Team member suggested using nuclear radiation to produce targeted genetic mutations in plants and animals, a concept that has potential applications in medical therapy, invasive plant control, and pest insect sterilization. Other ideas included using nuclear isotopes to produce very small, incredibly powerful nanobatteries; and even using a highly targeted nuclear explosion to divert or dissipate the energy of threatening weather systems such as typhoons and hurricanes.

Blue Skies

With a mission as big as the world itself, IDR Team 7B's members proceeded with a "sky's the limit" attitude. This blue-sky thinking, unfettered by the economic, regulatory, and practical constraints of typical research, produced ideas that could change the world.

Appendixes

List of Advanced Nuclear Technologies Preconference Tutorials

Advanced Nuclear Systems and Fuel Cycles
Podcast Released: September 5, 2013
Michael L. Corradini
Professor
Department of Engineering Physics
University of Wisconsin-Madison

Design and Fund a 3-Year Public–Private Initiative to Better Understand and Bridge the Perception/Reality Gap Between the Public and Nuclear Experts on the Risks of the Nuclear Enterprise and to Restore the Public Trust
Tutorial Released: September 12, 2013
Paul Slovic
President
Decision Research
Professor of Psychology
University of Oregon

Radionuclide Production with Reactors, Accelerators, and Generators
Tutorial Released: September 26, 2013
Jason S. Lewis
Vice Chairman for Research;
Chief, Radiochemistry and Imaging Sciences
Department of Radiology
Memorial Sloan-Kettering Cancer Center

Challenges to the Widespread Use of Radiopharmaceuticals for Diagnostic Imaging and Therapy
Tutorial Released: September 26, 2013
Markus B. Schwaiger
Professor
Technische Universität München

Why Radionuclides for Imaging and Therapy Are Essential for Modern Medicine
Tutorial Released: September 26, 2013
Wolfgang Weber
Chief, Molecular Imaging and Therapy Service; Director, Laurent and Alberta Gerschel Positron Emission Tomography Center
Department of Radiology
Memorial Sloan-Kettering Cancer Center

Define the Means to Promote U.S. Interests in the International Nuclear Power Field in an Era of Diminishing U.S. and Western European Influence
Tutorial Released: October 10, 2013
Richard K. Lester
Department Head
Nuclear Science and Engineering
Massachusetts Institute of Technology

Light-Water Reactor Fuel
Tutorial Released: October 10, 2013
David Petti
Fellow
Idaho National Lab

How the Widespread Use of Civilian Power and Associated Fuel Cycle Facilities Might Be Made Compatible with a World Free of Nuclear Weapons
Tutorial Released: October 24, 2013
Albert Carnesale
Chancellor Emeritus and Professor
University of California, Los Angeles

Approaches to Make Special Nuclear Materials (SNMs) More Easily Monitored and Detectable
Tutorial Released: October 31, 2013
Edward Blandford
Assistant Professor
University of New Mexico

Identify a New and Practical Application of Nuclear Phenomena for the Benefit of Humankind
Tutorial Released: October 31, 2013
Alan Waltar
Senior Advisor
Pacific Northwest National Laboratory

All tutorials are available at www.keckfutures.org.

Agenda

Friday, November 15, 2013

8:00 a.m.	Bus Pickup: Attendees are asked to allow ample time for breakfast at the Beckman Center; no food or drinks are allowed in the auditorium, which is where the welcome and opening remarks take place at 9:30.
8:30 a.m.	Registration (not necessary for individuals who attended Welcome Reception) Poster Session A Setup
8:30–9:30 a.m.	Breakfast
9:30–9:45 a.m.	**Welcome and Opening Remarks** Bruce B. Darling, NAS/NRC Executive Officer Richard A. Meserve, Chair NAKFI Steering Committee on Advanced Nuclear Technologies; President, Carnegie Institution for Science
9:45–10:45 a.m.	**Keynote Address** U.S. Secretary of Energy Ernest J. Moniz

10:45–11:00 a.m.	**Interdisciplinary Research (IDR) Team Challenge and Grant Program Overview** Richard A. Meserve, Chair, NAKFI Steering Committee on the Advanced Nuclear Technologies **Overview of W. M. Keck Foundation Grant Programs** Maria Pellegrini, Executive Director of Programs, W. M. Keck Foundation
11:00 a.m.–12:45 p.m.	Break/Poster Session A
12:45–2:00 p.m.	Lunch
2:00–5:30 p.m.	IDR Team Challenge Session 1
3:00–3:30 p.m.	Break
	Poster Session B Setup
5:30–7:00 p.m.	Reception/Poster Session B
7:00 p.m.	Bus Pickup: Attendees brought back to hotel.

Saturday, November 16, 2013

8:00 a.m.	Bus Pickup
8:15–9:00 a.m.	Breakfast
9:00–11:00 a.m.	IDR Team Challenge Session 2
11:00–11:30 a.m.	Break
11:30 a.m.–1:00 p.m.	IDR Team Challenge Preliminary Reports (5 to 6 minutes per group)
1:00–2:30 p.m.	Lunch
2:30–3:30 p.m.	**What's Your Big iDEA? (Interdisciplinary, Enthusiastic, Actionable, Suggestions)** Attendees give 2-minute pitches for IDR Team Challenge ideas to be explored with interested attendees
3:30–3:45 p.m.	Attendees sign up for iDEA groups
3:45–5:30 p.m.	IDR Team Challenge Session 3

5:30–7:00 p.m.	iDEA groups meet over dinner to explore challenges. (Meeting location assignments available at registration desk)
7:00 p.m.	Bus Pickup

Sunday, November 17, 2013

7:00 a.m.	Bus Pickup: Attendees who are departing for the airport directly from the Beckman Center are asked to bring their luggage to the Beckman Center. Storage space is available.
7:15–8:00 a.m.	Breakfast
7:15 a.m.	IDR Team Challenge Final Presentation Drop-Off: IDR Teams to drop off presentations at information/registration desk or upload to FTP site by 7:15 a.m. Taxi Reservations: Attendees are asked to stop by the information/registration desk to confirm their transportation to the airport or hotel.
8:00–9:30 a.m.	IDR Team Challenge Final Reports (8 to 10 minutes per group)
9:30–10:00 a.m.	Break
10:00–noon	IDR Team Challenge Final Reports (continued) (8 to 10 minutes per group) Q&A Across All Groups
Noon–3:00 p.m.	**Working Lunch/NAKFI inMotion**: Build on the momentum put in motion at the conference. Continue work on iDEA groups, regroup with assigned IDR Team, meet with others from like teams. Open forum session in Auditorium. Grant proposal brainstorm sessions. Staff on hand to answer questions about grant proposal process.

Lunch will be provided.

Participant List

Rodney M. Adams
Publisher
Atomic Insights

S. J. Adelstein
Paul C. Cabot Distinguished Professor of Medical Biophysics
Harvard Medical School

Joonhong Ahn
Professor
Nuclear Engineering
University of California, Berkeley

Nsikan Akpan
Science Writing Scholar
Science Communication
University of California, Santa Cruz

John S. Applegate
Executive Vice President for University Academic Affairs
Indiana University

Shahzeen Z. Attari
Assistant Professor
School of Public and Environmental Affairs
Indiana University

Jesse H. Ausubel
Director, Program for the Human Environment
The Rockefeller University

Yousry Y. Azmy
Professor & Department Head
Nuclear Engineering
North Carolina State University

Brandon P. Behlendorf
Senior Researcher
National Consortium for the Study of Terrorism and Responses to Terrorism
University of Maryland, College Park

Marissa Z. Bell
Graduate Student
Geography Department
SUNY University at Buffalo

Stephen T. Bell
Branch Head, Advanced Nuclear Reactor Design
Reactor Engineering Division, Code 08I
Office of Naval Reactors

Sujata K. Bhatia
Assistant Director of Undergraduate Studies
Assistant Dean
Biomedical Engineering
Harvard University

Edward D. Blandford
Assistant Professor
Farris Engineering Center
University of New Mexico

Ronald L. Boring
Human Factors Principal Scientist
Human Factors, Control, and Statistics Department
Idaho National Laboratory

Keith S. Bradley
Sr. Nuclear Engineer-Technical Director
Nuclear Engineering
Argonne National Laboratory

Robert L. Brent
Distinguished Professor of Pediatrics, Radiology & Patholgy
Research, Genetics & Pediatrics
Thomas Jefferson University, duPont Hospital for Children

Robert J. Budnitz
Research Scientist
Robert Budnitz, private consultancy

Peter C. Burns
Massman Professor and Director
Civil & Environmental Engineering & Earth Sciences, Chemistry & Biochemistry
University of Notre Dame

Carol J. Burns
Deputy Principal Associate Director
Science, Technology and Engineering
Los Alamos National Laboratory
Jeremy T. Busby
Senior Research Scientist
Nuclear Science and Engineering Directorate
Oak Ridge National Laboratory

Albert Carnesale
Chancellor Emeritus and Professor
University of California, Los Angeles

Richard E. Carson
Professor
Diagnostic Radiology and Biomedical Engineering
Yale University

Benjamin M. Chase
Nuclear Engineer
Irradiation Testing
Idaho National Laboratory

Thomas B. Cochran
Consulting Senior Scientist and former Director of the Nuclear Program
Natural Resources Defense Council, Inc. (NRDC)

Daniel G. Cole
Associate Professor and Interim Director of Nuclear Engineering
Mechanical Engineering and Materials Science
University of Pittsburgh

Graham P. Collins
Editor/science writer
Freelance

Jacinta C. Conrad
Assistant Professor
Chemical and Biomolecular Engineering
University of Houston

Lydia M. Contreras
Assistant Professor
Chemical Engineering
University of Texas-Austin

Michael L. Corradini
Professor
Department of Engineering Physics
University of Wisconsin-Madison

Carolyn Crist
Science Writing Scholar
Grady College of Journalism and Mass Communication
University of Georgia

Barbara J. Culliton
President
The Culliton Group/Editorial Strategies

Narasimhan Danthi
Program Director
National Heart, Lung, and Blood Institute
National Institues of Health

Bruce B. Darling
Executive Officer
National Research Council/ National Academy of Sciences

Joshua E. Daw
Research Scientist and Engineer
Irradiation Testing
Idaho National Laboratory

Anthony J. Di Pasqua
Assistant Professor of Pharmaceutical Sciences
Pharmaceutical Sciences
University of North Texas System College of Pharmacy

Matthew T. Domonkos
Senior Research Physicist
Directed Energy Directorate
Air Force Research Laboratory

Georges El Fakhri
Professor of Radiology; Director, Ctr for Advanced Medical Imaging Sciences Radiology; Nuclear Medicine and Molecular Imaging
Massachusetts General Hospital; Harvard Medical School

Frederic H. Fahey
Immediate Past-President
Div of Nuclear Medicine/Molecular Imaging
Society of Nuclear Medicine adn Molecular Imaging

Michael T. Fasullo
Research Scientist and Associate Professor
Nanobioscience
Research Foundation for SUNY on behalf of College of Nanoscale Sciences and Engineering

Rachel Feltman
Science Writing Scholar
New York University

Audeen W. Fentiman
Professor, Associate Dean
Nuclear Engineering
Purdue University

R. Scott Fletcher
Senior Scientist
Applied Research and Methods
U.S. Government Accountability Office

Michael J. Fluss
Sr. Scientist
Materials Science
Lawrence Livermore National Laboratory

John J. Gantnier
Mechanical Engineering Group Supervisor
Engineering
Bechtel Power Corporation

Megan Garcia
Program Officer
Nuclear Security Initiative
William & Flora Hewlett Foundation

William A. Garner
Laboratory Coordinator, Office of the Deputy Director General
Nuclear Sciences and Applications
International Atomic Energy Agency

Elisabeth A. Gilmore
Assistant Professor
School of Public Policy
University of Maryland

Sundaresan Gobalakrishnan

Assistant Professor
Radiology
Virginia Commonwealth University

Julia R. Greer
Professor of Materials Science and Mechanics
Division of Engineering and Applied Sciences
Caltech

Patrick Hahn
Science Writing Scholar
Johns Hopkins University

Mark B. Halper
Journalist/Writer/Editor/Author/Blogger
Freelance
CBS, *The Guardian*, Weinberg Foundation

David J. Harris
PNAS
National Academy of Sciences

Anne Heberger Marino
Program Officer
National Academies Keck *Futures Initiative*

Kathryn A. Higley
Professor and Head
Nuclear Engineering and Radiation Health Physics
Oregon State University

Seth A. Hoedl
Harvard Law School

John F. Holzrichter
President
Physical-Insights Associates

Jacob M. Hooker
Assistant Professor
Martinos Center for Biomedical Imaging
Harvard Medical School/MGH

Kate Horowitz
Science Writing Scholar
AAP, Krieger School of Arts and Sciences
Johns Hopkins University

Peter Hosemann
Assistant Professor
Nuclear Engineering
University of California, Berkeley

Hedvig Hricak
Chair
Department of Radiology
Memorial Sloan-Kettering Cancer Center

Thomas H. Isaacs
E.O. Lawrence Livermore National Laboratory Visiting Scientist

Efstathios Karathanasis
Assistant Professor
Radiology and Biomedical Engineering
Case Western Reserve University

Cristen A. Kelly
Associate Program Officer
National Academies Keck *Futures Initiative*

Annie B. Kersting
Director Glenn T. Seaborg Institute
Physical & Life Sciences
Lawrence Livermore National Laboratory

Kevin J. Kramer
National Ignition Facility
Lawrence Livermore National Laboratory

Alexa Kurzius
Science Writing Scholar
New York University

Jae W. Kwon
Director and Associate Professor
Center for Advanced Nuclear Technology and Micro Integrated Systems (CANTMIS)
University of Missouri - Columbia

Rachel Lesinski
Program Associate
National Academies Keck *Futures Initiative*

Richard K. Lester
Japan Steel Industry Professor and Head
Department of Nuclear Science and Engineering
Massachusetts Institute of Technology

Jason S. Lewis
Emily Tow Jackson Chair in Oncology, Vice Chairman for Research; Chief, Radiochemistry and Imaging Sciences
Department of Radiology
Memorial Sloan-Kettering Cancer Center

Jie Lian
Associate professor
Mechanic, Aerospace & Nuclear Engineering
Rensselaer polytechnic institute

Li Liu
Associate Professor
Mechanical, Aerospace, and Nuclear Engineering
Rensselaer Polytechnic Institute

Wei Lu
Professor
Mechanical Engineering
University of Michigan, Ann Arbor

Digby D. Macdonald
Professor in Residence
Nuclear Engineering
University of California, Berkeley

Jyoti Madhusoodanan
Science Writing Scholar
Science Communication Program
University of California, Santa Cruz

Mark W. Maier
Distinguished Engineer
Electronic and Systems Division
The Aerospace Corporation

Annalisa Manera
Associate Professor
University of Michigan

Samuel S. Mao
Adjunct Professor
Department of Mechanical Engineering
University of California, Berkeley

Raymond P. Mariella
Senior Scientist
Lawrence Livermore National Laboratory

Brad Marston
Professor
Physics
Brown University

Charles McCombie
President
Arius Association

Michael A. McDonald
Nuclear Medicine Resident
Nuclear Medicine
Johns Hopkins University

Martha L. Mecartney
Professor of Chemical Engineering and Materials Science and Engineering
Chemical Engineering and Materials Science and Engineering
University of California, Irvine

Richard A. Meserve
President
Carnegie Institution for Science

Catherine H. Middlecamp
Professor
Nelson Institute for Environmental Studies
University of Wisconsin-Madison

Warren "Pete" Miller
TEES Distinguished Research Professor
Texas A & M University System

Amit Misra
Laboratory Fellow
Director, Energy Frontier Research Center
Los Alamos National Laboratory

Jessica Morrison
Science Writing Scholar

Jodi Murphy
Science Writing Scholar
Health and Medical Journalism
University Georgia

Hamid Najib
Information Technology and Program Support Specialist
National Academies Keck *Futures Initiative*

William H. Newell
Executive Director
Association for Interdisciplinary Studies

Jessica M. Orwig
Science Writing Scholar
Veterinary Medicine and Biomedical Sciences
Texas A&M University

Chris Palmer
Conference Summary Writer
National Cancer Institute

Maria Pellegrini
Executive Director, Programs
W.M. Keck Foundation

Mark T. Peters
Deputy Laboratory Director for Programs
Office of the Director
Argonne National Laboratory

Per F. Peterson
Professor
Nuclear Engineering
University of California, Berkeley
Todd E. Peterson
Associate Professor
Radiology and Radiological Sciences
Vanderbilt University

Bojan Petrovic
Professor
Nuclear and Radiological Engineering
Georgia Institute of Technology

David Petti
Fellow
Idaho National Laboratory

Jonathan K. Pokorski
Asst. Professor
Macromolecular Science and Engineering
Case Western Reserve University

Vikas Prakash
Professor
Mechanical and Aerospace Engineering
Case Western Reserve University

Daniel A. Pryma
Assistant Professor of Radiology
Radiology
University of Pennsylvania

Kathleen L. Purvis-Roberts
Associate Professor of Chemistry & Environmental Science
W.M. Keck Science Department
Pitzer College

Shriram Ramanathan
Associate Professor
Applied Physics/Materials Science
Harvard University

William C. Regli
Associate Dean for Research; Professor of Computer and Information Science
Computer & Information Science
Drexel University

Robert Rosner
Professor
Science and Security Board
Bulletin of the Atomic Scientists

Naveena Sadasivam
Science Writing Scholar
New York University

Natalia V. Saraeva
Nuclear Engineer
Nuclear Engineering
Argonne National Laboratory

Beth-Anne Schuelke-Leech
Senior Research Fellow
Energy From Thorium Foundation

Markus Schwaiger
Professor
Technische Universität München

Raymond J. Sedwick
Associate Professor
Aerospace Engineering
University of Maryland

Kelly Servick
Science Writing Scholar
Science

Aaron J. Simon
Group Leader: Energy
Atmosphere Earth and Energy Division
Lawrence Livermore National Laboratory

Francis Slakey
Associate Director of Public Affairs
American Physical Society

Alexander H. Slocum
Pappalardo Professor of Mechanical Engineering
Mechanical Engineering
Massachusetts Institute of Technology

Tanju Sofu
Department Manager
Nuclear Engineering Division
Argonne National Laboratory

Kumar Sridharan
Distinguished Research Professor
Nuclear Engineering and Engineering Physics
University of Wisconsin-Madison

Nicholas St. Fleur
Science Writing Scholar
Science Communication
University of California, Santa Cruz

Marius Stan
Senior Computational Energy Scientist
Nuclear Engineering
Argonne National Laboratory

Susan M. Stevens-Adams
Cognitive Psychologist
Risk and Reliability Analysis
Sandia National Laboratories

Neal Stewart
Ivan Racheff Chair of Excellence Professor in Plant Molecular Genetics
Plant Sciences
University of Tennessee

Daniel Stokols
Chancellor's Professor
Department of Planning, Policy, and Design and Department of Psychology and Social Behavior; Program in Public Health and Department of Epidemiology
University of California, Irvine

Kimberly A. Suda-Blake
Senior Program Director
National Academies Keck *Futures Initiative*

Julie L. Sutcliffe
Associate Professor
Internal Medicine and Biomedical Engineering
University of California, Davis

Mark Sutton
Nuclear Fuel Cycle Program Leader (acting)
Energy Security Program
Lawrence Livermore National Laboratory

Mitra L. Taheri
Hoeganaes Assistant Professor
Materials Science & Engineering
Drexel University

Yuan-Chuan Tai
Associate Professor; Director (Interim) of Radiological Chemistry and Imaging Laboratory
Mallinckrodt Institute of Radiology
Washington University in St. Louis

Mercedes V. Talley
Program Director
W.M. Keck Foundation

Raymond Thornton
Vice Chair for Quality, Safety, and Performance Improvement
Department of Radiology
Memorial Sloan Kettering Cancer Center

Bernhard R. Tittmann
Professor
Engineering Science and Mechanics
The Pennsylvania State University

Pallavi Tiwari
Research Assistant Professor
Biomedical Engineering
Case Western Reserve University

Bao H. Truong
Reactor Safety Analyst
Reactor Safety and Analysis
TerraPower LLC

Izabela Tworowska
Chief Science Officer
RadioMedix Inc. ; RITA Foundation Houston

Kenan Unlu
Professor and Director
Radiation Science and Engineering Center and Dept. Mech. and Nuclear Engin.
Pennsylvania State University

Michael van Dam
Assistant Professor
Molecular & Medical Pharmacology
University of California, Los Angeles

Satish Viswanath
Research Assistant Professor
Biomedical Engineering
Case Western Reserve University

Alan Waltar
Senior Advisor (Retired)
Pacific Northwest National Laboratory

Wolfgang Weber
Chief, Molecular Imaging and Therapy Service; Director, Laurent and Alberta Gerschel Positron Emission Tomography Center
Department of Radiology
Sloan-Kettering Insitute for Cancer Research

Frank J. Wessel
Scientist (recall)
Physics and Astronomy
University of California, Irvine

Andrew S. Whittaker
Professor; MCEER Director
Civil, Structural and Environmental Engineering
University at Buffalo

Paul P.H. Wilson
Professor
Engineering Physics
University of Wisconsin-Madison

Brian D. Wirth
Governor's Chair Professor of Computational Nuclear Engineering
Nuclear Engineering
University of Tennessee

Chadwick L. Wright
Assistant Professor of Radiology
Department of Radiology, Division of Molecular Imaging and Nuclear Medicine
The Ohio State University Wexner Medical Center

Jianzhong Wu
Professor
Department of Chemical and Environmental Engineering
University of California, Riverside

Julianne Wyrick
Science Writing Scholar
Grady College of Journalism and Mass Communication
University of Georgia

Weian Zhao
Assistant professor
Pharmaceutical Sciences
University of California, Irvine

Steven J. Zinkle
Governor's Chair
Department of Nuclear Engineering
University of Tennessee