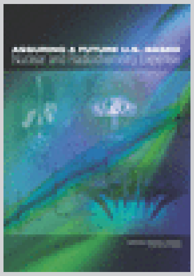

Assuring a Future U.S.-Based Nuclear and Radiochemistry Expertise

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ASSURING A FUTURE U.S.-BASED Nuclear and Radiochemistry Expertise

Committee on Assuring a Future U.S.-Based Nuclear Chemistry Expertise

Board on Chemical Sciences and Technology

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Cover art: Images show the range of applications that utilize nuclear and radiochemistry expertise, clockwise from bottom right; nuclear energy (Cherenkov radiation), medical imaging (Positron Emission Tomography abdominal scan), nuclear security (atmospheric testing), and in the center, environmental management (chart of radionuclides).
Courtesy: Los Alamos National Laboratory Omega West reactor (Cherenkov radiation); Abdominal Imaging (Positron Emission Tomography scan); National Nuclear Security Administration Nevada Site Office (atmospheric testing); and Brookhaven National Laboratory (chart of radionuclides).

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Preface

The critical U.S. need for nuclear and radiochemistry expertise in areas such as nuclear medicine, nuclear power, nuclear security, and radioactive waste clean-up and disposal, combined with a past decline in the number of students graduating in this field drove the request for this comprehensive examination of the current and anticipated supply and demand for expertise, including types and levels of skills, in the United States for medicine, energy, defense, and environment.

The Committee on Assuring a Future U.S.-Based Nuclear Chemistry Expertise was charged (Appendix A) with examining the demand for nuclear chemistry expertise in the United States compared with the production of experts with these skills, and to discuss possible approaches for ensuring adequate availability of these skills, including necessary science and technology training platforms.

The committee of 13 members (Appendix B) was convened from approximately January 2011 through December 2011, and met in person four times (Appendix C). Expertise included those with experience in nuclear and radiochemistry, including backgrounds in nuclear medicine, nuclear power, nuclear security, and environmental management and in research management, university administration, scientific workforce and training indicators, and development of advanced educational programs.

Acknowledgment of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the NRC's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

We wish to thank the following individuals for their review of this report:

Burt Barnow, The George Washington University, Washington, D.C.
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Paul Mantica, Michigan State University, East Lansing
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Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by **Edward B. Perrin**, University of Washington, Seattle, and **Charles P. Casey**, University

of Wisconsin, Madison. Appointed by the National Research Council, they were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Contents

Appendixes

Acronyms

AAAS	American Association for the Advancement of Science
AAS	Associates of Applied Science Degree
AAU	American Association of Universities
ACA	Arms Control Association
ACC	American Chemistry Council
ACS	American Chemical Society
ACTINET-I3	European Commission Integrated Infrastructure Initiative for Actinide Science
APS	American Physical Society
ASTC	Association of Science and Technology Centers
BER	Office of Biological and Environmental Remediation
BES	U.S. Department of Energy's Office of Basic Energy Sciences
BLS	Bureau of Labor Statistics
BNFL	British Nuclear Fuels Limited
BNL	Brookhaven National Laboratory
BTSI	Bio-tech Systems, Inc
CAES	Center for Advanced Energy Studies
CEA	Alternative Energies and Atomic Energy Commission (Commissariat à l'Énergie Atomique et aux Énergies Alternatives)
CEGB	Central Electricity Generating Board
CFEN	Council for Education and Training in Nuclear Energy (Conseil des Formations en Energie Nucléaire)
CIP	Classification of Instructional Program
CMS	Centers for Medicare and Medicaid Services
COREs	Centers of Research and Educations

CRESP	Consortium for Risk Evaluation with Stakeholder Participation
CRR	Centre for Radiochemistry Research
CT	Computerized Axial Tomography
CTBT	Comprehensive Nuclear-Test-Ban Treaty
CTBTO	Comprehensive Nuclear-Test-Ban Treaty Organization
DATSD(NM)	Deputy Assistant to the Secretary of Defense (Nuclear Matters)
DGR	Directory of Graduate Research
DHS	U.S. Department of Homeland Security
DNCT	Division of Nuclear Chemistry and Technology
DNDO	DHS Domestic Nuclear Detection Office
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
DOE-EM	DOE Office of Environmental Management
DOE-LM	DOE Office of Legacy Management
DOE-NP	DOE Office of Nuclear Physics
DSB	Defense Science Board
DTC	Doctoral Training Centre
DTRA	Defense Threat Reduction Agency
EDF	Electricity of France (Electricité de France)
EFRC	Energy Frontier Research Center
EIA	Energy Information Administration
EM	environmental management
EPA	U.S. Environmental Protection Agency
FDG	Fluorodeoxyglucose
FDA	U.S. Food and Drug Administration
FIU	Florida International University
FRIB	Facility for Rare Isotope Beams
GAO	Government Accountability Office
HEGIS	Higher Education General Information Survey
IAEA	International Atomic Energy Agency
IMV	Medical Information Division
INEST	Institute of Nuclear Energy Science and Technology
INL	Idaho National Laboratory

IOM	Institute of Medicine
IPEDS	Integrated Postsecondary Education Data System
IRP	integrated research projects
ITWG	International Technical Working Group on Nuclear Smuggling
IUP	integrated university program
J-ACTINET	Japan Integrative Infrastructure Initiative for Actinide Science
LANL	Los Alamos National Laboratory
LEP	lifetime extension program
LLNL	Lawrence Livermore National Laboratory
MARLAP	Multi-Agency Radiological Laboratory Analytical Protocols
MRI	Magnetic Resonance Imaging
MU	University of Missouri
NAE	National Academy of Engineering
NAMP	National Analytical Management Program
NCES	National Center for Education Statistics
NCSL	National Conference of State Legislatures
NEI	Nuclear Energy Institute
NEUP	Nuclear Energy University Program
NIF	National Ignition Facility
NIH	National Institutes of Health
NNL	National Nuclear Laboratory
NNSA	National Nuclear Security Administration
NP	Office of Nuclear Physics
NPT	Nuclear Nonproliferation Treaty
NRC	National Research Council
NSAC	Nuclear Science Advisory Committee
NSB	National Science Board
NSF	National Science Foundation
NSTC	National Science and Technology Council
NTNF	National Technical Nuclear Forensics
NTNFC	National Technical Nuclear Forensics Center
NUCL	Global Nuclear Energy Index Fund
OMB	Office of Management and Budget
ORISE	Oak Ridge Institute for Scientific Education

OTID	Office of Technology Innovation and Development
PET	Positron Emission Tomography
PQDT	ProQuest Dissertations and Theses Database
QMU	quantification of margins and uncertainties
R&D	research and development
RHIC	Relativistic Heavy Ion Collider
RII	Radiochemistry and Imaging Instrumentation
RPSC	Radiopharmaceutical Sciences Council
SED	Survey of Earned Doctorates
S&E	science and engineering
SJSU	San José State University
SNM	Society of Nuclear Medicine
SOC	Standard Occupational Classifications
SPECT	Single Photon Emission Computed Tomography
SRS	Society of Radiopharmaceutical Sciences
SSP	Stockpile Stewardship Program
TNF	Technical Nuclear Forensics
UKAEA	United Kingdom Atomic Energy Authority
USNRC	U.S. Nuclear Regulatory Commission
WNA	World Nuclear Association
WSU	Washington State University

Executive Summary

The growing use of nuclear medicine, the potential expansion of nuclear power generation, and the urgent needs to protect the nation against external nuclear threats, to maintain our nuclear weapons stockpile, and to manage the nuclear wastes generated in past decades, require a substantial, highly trained, and exceptionally talented workforce. This report analyzes the demand for and supply of nuclear and radiochemistry experts, a major component of this workforce (Chapters 1, 2, and 8). None of these areas, considering a range of reasonable scenarios looking to the future, is likely to experience a decrease in demand for expertise (Chapters 4-7). However, many in the current workforce are approaching retirement age and the number of students opting for careers in nuclear and radiochemistry has decreased dramatically over the past few decades. In order to avoid a gap in these critical areas, increases in student interest in these careers, in the research and educational capacity of universities and colleges, and sector specific on-the-job training will be needed (Chapters 3 and 9). Concise recommendations are given for actions to avoid a shortage of nuclear and radiochemists in the future (Chapter 10).

1

Introduction

There is a distinguished history of discoveries, achievements, and societal impact for nuclear and radiochemistry (defined in Box 1-1). After the discovery of radioactivity by Antoine Henri Becquerel and Marie and Pierre Curie, who jointly received the Nobel Prize in physics in 1903 (Nobelprize.org 2012a), and of radium and polonium by Marie Curie, who received the Nobel Prize in chemistry in 1911 (Nobelprize.org 2012b), interest in nuclear and radiochemistry and the potential uses of radioactive materials grew significantly (see Figure 1-1).

In 1937 Glenn Seaborg received his Ph.D. in nuclear chemistry from the University of California, Berkeley, and in 1939 E.O. Lawrence, also at UC Berkeley, won the Nobel Prize in physics for inventing the cyclotron (Nobelprize.org 2012c). A significant development in medicine was the use of radioisotopes as tracers to study chemical processes by George de Hevesy, for which he received the Nobel Prize in chemistry in 1943 (Nobelprize.org. 2012d). In 1951 Seaborg jointly earned the Nobel Prize in chemistry with Edwin McMillan for discovery of the transuranium elements and elucidation of their chemistry (Nobelprize.org 2012e). By the 1950s, radioactivity and radioactive elements were being applied in many fields such as medicine, energy, defense, and environmental monitoring.

The Atomic Energy Act signed into law in 1954 established the national laboratories, many on university campuses across the United States. As a result, the field of nuclear and radiochemistry developed from the study of the fundamental physical and chemical properties of radioactivity, which had mainly been applied in national defense, to applications in a range of areas, including cancer treatment, electricity production, and study of the impacts of large-scale events such as the use of nuclear weapons at the end of World War II.

The field of nuclear and radiochemistry has changed significantly since the mid-1960s, due to both positive and negative circumstances. U.S. de-

BOX 1-1 THE DISCIPLINE: NUCLEAR AND RADIOCHEMISTRY

For this report, the committee drew on two seminal textbooks for definitions of the discipline. The first, *Nuclear Chemistry: Theory and Applications* (Choppin and Rydberg 1980, page vii), defines nuclear chemistry as follows:

> There is no universally accepted definition for the term "nuclear chemistry." For purposes of our text we regard nuclear chemistry in its broadest context as an interdisciplinary subject with roots in physics, biology, and chemistry. The basic aspects include among others (i) nuclear reactions and energy levels, (ii) the types and energetics of radioactive decay, (iii) the formation and properties of radioactive elements, (iv) the effect of individual isotopes on chemical and physical properties, and (v) the effects of nuclear radiation on matter. Research in (i) and (ii) is often indistinguishable in purpose and practice from that in nuclear physics, although for nuclear chemists chemical techniques may play a significant role. (iii) and (iv) can be classified as *radiochemistry* and *isotope chemistry,* while (v) falls in the classification of *radiation chemistry*.
>
> Applied aspects of nuclear chemistry involve production of radioactive isotopes, radiation processing, radiation conservation of foods, etc., as well as all parts of the nuclear fuel cycle such as uranium recovery, isotope separation, reactions in the fuel elements, processing of spent fuel elements, waste handling, and effects of radiation on reactor materials. Radiation health aspects and techniques for remote control are other important fields.
>
> Knowledge in nuclear chemistry is an essential tool for research, development, and control in many areas of chemistry and technology (tracer methods, activation analysis, control gauges in industry, etc.), medicine (radiopharmaceuticals, nuclear medicine, radioimmuno assay, etc.), geology, and archeology (radioactive dating).

The second book, *Nuclear and Radiochemistry* (Friedlander et al. 1981, p. v), takes a similarly broad view of the discipline:

> In adopting the present title of the book in 1955 we gave explicit recognition to a dichotomy in the field and in the audience addressed; a dichotomy that has probably become even more pronounced since then. The book is written as an introductory text for two broad groups: nuclear chemists, that is, scientists with chemical background and chemical orientation whose prime interest is the study of nuclear properties and nuclear reactions; and radiochemists, that is, chemists concerned with the

fense modifications after World War II led to the curtailment of plutonium production beginning in 1964 and by 1972 eight of nine production reactors had been shut down, leaving significant cleanup issues (DOE 2011a). In addition, concerns about nuclear safety and security due to atmospheric testing of nuclear weapons and reactor accidents at Three Mile Island in 1979 and Chernobyl in 1986, as well as the attraction of new areas such as materials and nanoscience, have resulted in declining interest in nuclear and radiochemistry.

chemical manipulation of radioactive sources and with the application of radioactivity and other nuclear phenomena to chemical problems (whether in basic chemistry or in biology, medicine, earth and space sciences, etc.). Despite the apparently growing division between these two audiences, individuals have always moved fairly freely from one field to the other, and we continue to feel that nuclear chemistry and radiochemistry interact strongly with each other and indeed are so interdependent that their discussion together is almost necessary in an introductory text.

The Workforce: Nuclear and Radiochemists

As a research area or academic discipline, nuclear and radiochemistry is considered a subarea of chemistry. Nuclear and radiochemists are chemists who hold one or more degrees in chemistry and have taken additional specialized courses and conducted laboratory work in nuclear and radiochemistry. They typically work in an organization's chemistry department or division.

There is no listing for nuclear and radiochemists in the Standard Occupational Classification (SOC) system.[1] Nuclear and radiochemists are part of the broader occupation of "chemists" (SOC code 19-2031), as are nuclear physicists part of the occupation of "physicists" (SOC code 19-2012). However, there is a classification for nuclear engineers (SOC code 17-2161), who, according to the Bureau of Labor Statistics, "conduct research on nuclear engineering projects or apply principles and theory of nuclear science to problems concerned with release, control, and use of nuclear energy and nuclear waste disposal" (BLS 2010). Other broad categories that may include nuclear and radiochemists (especially at the bachelor's degree level) are nuclear technicians (SOC code 19-4051), nuclear medicine technologists (SOC code 29-2033), and nuclear power plant operators (SOC code 51-8011).

For the purposes of this report, the committee defines individuals employed as nuclear and radiochemists as those who work on projects that apply the principles and theory of nuclear and radiochemistry in basic research and in applications including nuclear energy, medicine, weapons, and waste disposal.

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[1] For more information, see the Bureau of Labor Statistics website: www.bls.gov/soc/ [accessed June 30, 2012].

At the same time, there has been a generally positive interest in applications of nuclear and radiochemistry. For example, another outcome of the Atomic Energy Act of 1954 was the creation of the discipline of nuclear medicine in the use of radioisotopes to label molecules for research and development of radiopharmaceuticals for diagnostic imaging (most notably positron emission tomography) and therapy. As a result, the estimated number of radiological and nuclear medicine procedures performed in the United States to diagnose diseases such as cancer and heart disease grew

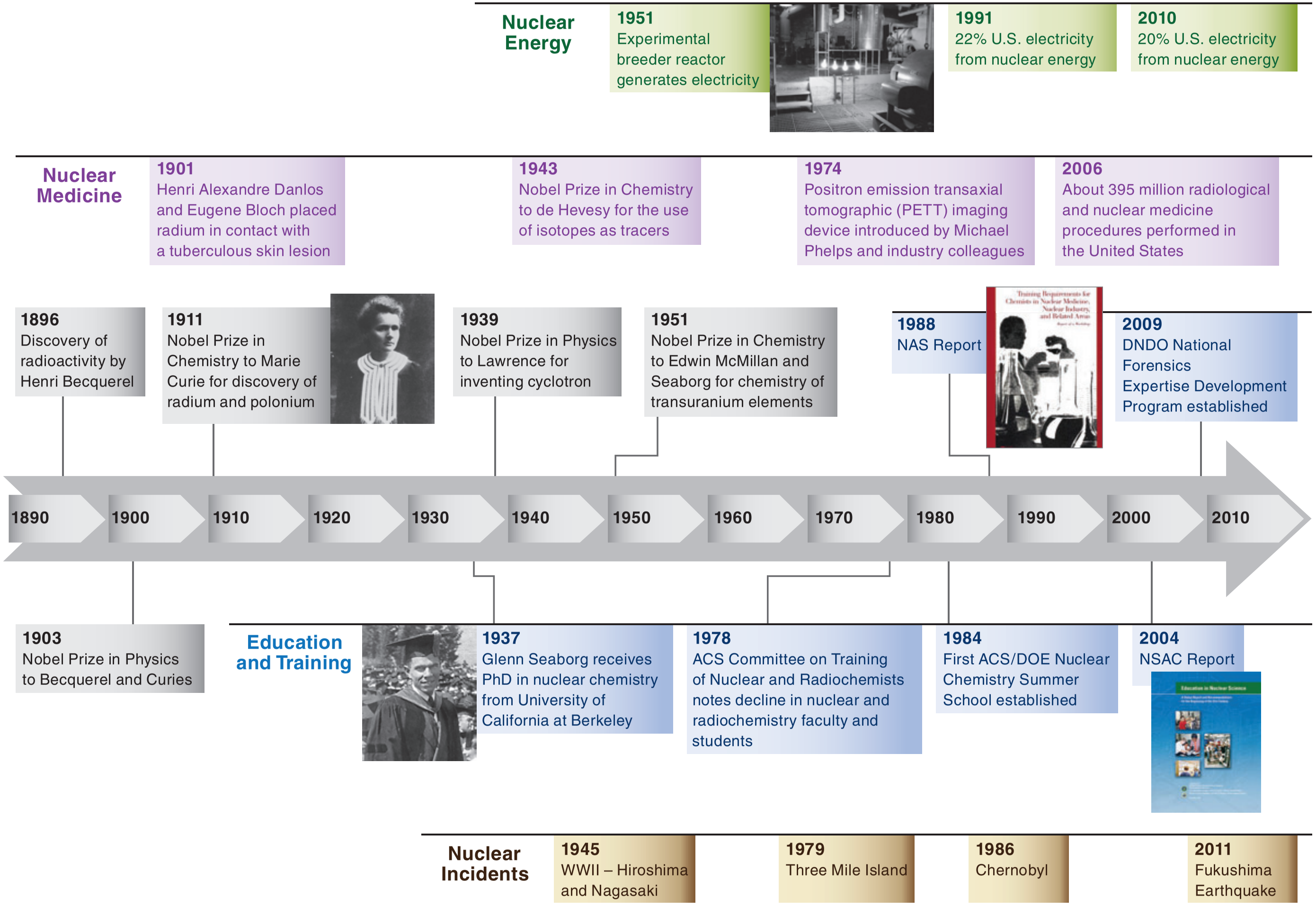

FIGURE 1-1 Milestones in Nuclear and Radiochemistry.

SOURCES: NRC 1988; Yates 1993; Peterson 1997; Argonne National Laboratory 2012; DOE/NSF 2004; DOE 2011a,b; EIA 2011a,b; Kentis 2011; Nobelprize.org 2012a,b,e; NSF 2011; SNM 2011; UC Berkeley 2012.

from approximately 25 million in 1950 to 395 million in 2006 (including mammographic examinations, but not dental radiographic exams) (Mettler et al. 2009).

Furthermore, despite the fact that nuclear power often receives negative press coverage and no new U.S. power plants have been built since the 1970s, nuclear energy has been a stable source of U.S. electricity since the 1980s, and in 2010 supplied approximately 20 percent of the U.S. total (EIA 2011a). In a March 2011 poll, 57 percent of Americans said they favor using nuclear power as a source of electricity even in the wake of the 2011 earthquake in Japan and its impacts on the Fukushima Daiichi power plant (Jones 2011).

ORIGINS OF THIS STUDY

Since the 1970s, reports have raised concerns about the state of the expertise pipeline in nuclear and radiochemistry skills, especially at the Ph.D. level. A steadily declining number of academic staff has resulted in a decrease in the number of both qualified U.S. citizens in the field and research programs at U.S. colleges and universities that produce experts in nuclear security, medicine, energy, environmental management, and basic research.

In 1978, the Committee on Training of Nuclear and Radiochemists—a committee of the American Chemical Society's (ACS) Division of Nuclear Chemistry and Technology (DNCT)—first noted a decline in nuclear and radiochemistry faculty and students in chemistry departments (ACS 1978), as indicated by the number of nuclear chemistry Ph.D.s reported in the National Science Foundation (NSF) annual Survey of Earned Doctorates (SED).[1] Between 1960 (the first year nuclear chemistry appeared on the SED questionnaire) and 1971, the number of Ph.D.s awarded each year in nuclear chemistry in the United States grew from 13 to 36, but then fell back to 13 in 1978 and, 10 years later, 7 (NSF 2011).

One of the first initiatives to attract and retain undergraduate student interest in the field of nuclear and radiochemistry (a direct result of the ACS Committee on Training of Nuclear and Radiochemists recommendations) that still exists today is the Nuclear Chemistry Summer Schools program, supported by the U.S. Department of Energy (DOE). The program began in 1984, first hosted in the Nuclear Science Facility at San José State Univer-

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[1] SED data are based on the selection of "nuclear chemistry" as a subfield of study on the questionnaire. See Survey of Earned Doctorates, https://webcaspar.nsf.gov/ [accessed June 29, 2012].

sity (SJSU) and subsequently expanded to Brookhaven National Laboratory (BNL) (see Box 9-1) (Peterson 1997; Clark 2005; Kinard and Silber 2005).

Shortly thereafter, a National Research Council workshop report on *Training Requirements for Chemists in Nuclear Medicine, Nuclear Industry, and Related Areas* (NRC 1988) similarly noted the decline in chemistry expertise. The report called for remedial measures "to alleviate the serious shortage and to ensure a future adequate supply of scientists with nuclear and radiochemical backgrounds and knowledge" and recommended the following (NRC 1988, p.6):

1. Increase the coverage of nuclear and radiochemical concepts and techniques in undergraduate courses to provide chemists with a basic understanding of the field and its applications to science and technology.[2]
2. Establish Young Investigator Awards for tenure-track faculty at universities, with at least five such awards to be given, each for a 5-year period.
3. Establish training grants and postdoctoral fellowships.
4. Establish a small number of training centers at universities and/or national laboratories for short courses in nuclear and radiochemistry and for retraining scientists and technologists with backgrounds in other areas. Support for the training centers should come in part from the industries and enterprises that depend on the trained personnel.
5. Establish a second summer school in nuclear chemistry for undergraduates at an eastern U.S. site [to augment the DOE-funded SJSU program].[3]
6. Ensure adequate funding for research from the DOE, National Institutes of Health (NIH), National Science Foundation (NSF), Department of Defense (DOD), and other federal agencies to maintain the continued vigor of the field at universities and national laboratories. In particular, identify a specific program at NSF to receive proposals in the field of nuclear and radiochemistry.

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[2] The American Chemical Society (ACS) has a certification program for undergraduate degrees in chemistry. Requirements include coursework for students in the core areas of chemistry defined as analytical, bio-, inorganic, organic, and physical. Although nuclear chemistry is the fundamental basis of chemistry, it is not specified in the ACS certified degree requirements. For more information, see www.acs.org [accessed June 29, 2012].

[3] In 1989 DOE established a second summer school for undergraduates at Brookhaven National Laboratory in New York (Yates 1993).

More broadly, there has been concern about the supply of nuclear science and engineering expertise in general (NRC 1990). Because nuclear chemistry accounts for a relatively small portion of nuclear science and engineering degrees (Figure 1-2) it is more vulnerable to declines in the numbers of degree holders. In fact, by 2003 the number of nuclear chemistry Ph.D.s had dropped so low (to four) that the category was removed from the SED questionnaire the following year, making it difficult to continue tracking numbers of degree holders in this discipline.

Nuclear and radiochemistry needs cannot simply be filled by transfers from the larger groups of engineering and physics degree holders. Much of the chemistry involved in separating actinides, preparing reagents for nuclear medicine, and removing radioactive materials from the environment requires knowledge of synthetic, analytical, and other aspects of chemistry, informa-

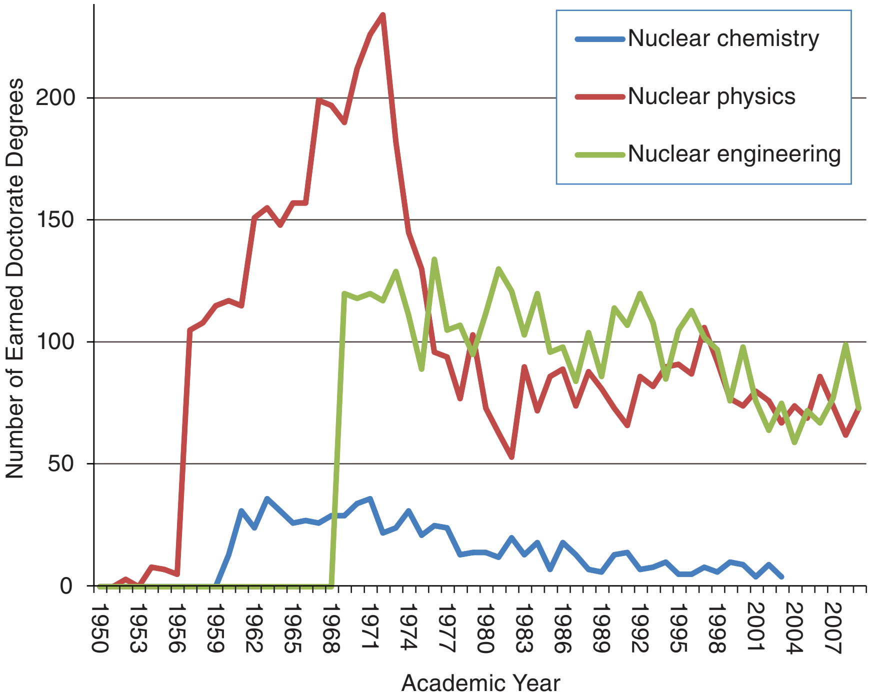

FIGURE 1-2 Number of Ph.D.s per year in selected nuclear science and engineering disciplines, 1950–2007.
NOTE: Survey of Earned Doctorates stopped counting nuclear chemistry degrees after 2003.
SOURCE: NSF (2011).

tion that is well beyond the content of most doctoral programs in nuclear engineering or nuclear physics.

Furthermore, degrees in nuclear and radiochemistry are only a very small part of overall numbers in the field of chemistry (doctorates shown in Table 1-1), and, as with engineering and physics degree holders, expertise in this area cannot simply be filled in by the larger number of degree holders in chemistry, because most chemistry courses and laboratory work do not typically include the specialized knowledge in nuclear reactions and decay modes, chemical reactions and chemical properties of radioactive elements and isotopes, or radiolytic processes caused by ionizing radiation produced by nuclear processes.

Chemistry was included in a report of the DOE/NSF Nuclear Science Advisory Committee, *Education in Nuclear Science* (DOE/NSF 2004), with the following recommendations to the DOE, NSF, and larger nuclear science community:

1. Outreach: Create a Center for Nuclear Science Outreach (highest priority).
2. Ph.D. Production: Increase the number of new Ph.D.s in nuclear science by 20 percent over the next 5–10 years.

TABLE 1-1 Trend Data from 2009 National Science Foundation Survey of Earned Doctorates for the Field of Chemistry and Its Associated Subfields

Doctorate recipients, by subfield of study: 1999–2009

Subfield of study[a]	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Chemistry	2,132	1,989	1,982	1,923	2,040	1,986	2,126	2,362	2,324	2,247	2,398
Analytical chemistry	333	326	334	302	339	323	363	367	397	371	363
Inorganic chemistry	279	221	279	250	264	240	256	267	273	299	331
Medicinal/pharmaceutical chemistry[b]	131	107	115	99	110	113	110	150	na	na	na
Nuclear chemistry	10	9	4	9	4	na	na	na	na	na	na
Organic chemistry	563	525	523	523	557	541	603	624	652	640	688
Physical chemistry	310	271	285	303	321	264	298	376	327	331	320
Polymer chemistry	95	107	107	102	109	116	119	134	122	106	119
Theoretical chemistry	56	52	40	48	49	54	57	86	86	80	85
Chemistry, general	196	261	203	202	184	198	191	211	309	274	304
Chemistry, other	159	110	92	85	103	137	129	147	158	146	188

ABBREVIATIONS: na, not applicable (the field was not on the questionnaire's specialties list for that year).

[a] Field groupings may differ from those in reports published by federal sponsors of the Survey of Earned Doctorates.

[b] This field was removed from the taxonomy in 2007. Graduates who indicated this field in 2007 are represented in the counts for Chemistry, other.

SOURCE: Adapted from NSF (2010), Table 14.

3. Diversity and Professional Development: Enhance participation of women and people of underrepresented backgrounds.
4. Undergraduate Education:
    - Establish a third summer school for nuclear chemistry modeled after the two existing schools;
    - Establish a community-developed recognition award for mentoring; and
    - Establish an online nuclear science instructional materials database;
5. Graduate and Postdoctoral Training:
    - Establish graduate education and postdoctoral training;
    - Shorten the median time to a Ph.D. degree;
    - Develop graduate fellowships in physical sciences (including nuclear science) (this is an endorsement of Secretary of Energy Advisory Board 2003 recommendation);
    - Establish new training grant opportunities; and
    - Establish prestigious postdoctoral fellowships with funding from NSF and DOE.

Since 2008, new efforts have been launched to increase the number of students in nuclear science and engineering in general. For example, DOE created the Nuclear Energy University Program (NEUP) (DOE 2011c), which provides funding for both research and student scholarships and fellowships at U.S. colleges and universities. NEUP is aimed mainly at nuclear engineering, but awards are open to students in nuclear-related fields, which include radiochemistry, health physics, nuclear physics, and other fields of engineering. In addition, the Department of Homeland Security's Domestic Nuclear Detection Office (DNDO) has been leading a joint effort with DOE, DOD, and others to support the nuclear science expertise pipeline and provide a stable foundation to cultivate and maintain a highly qualified technical nuclear forensics (TNF) workforce, which has a larger chemistry component than NEUP (Kentis 2011).

These recent efforts, together with programs begun in the 1980s, appear to be having a positive effect in bolstering the current and future availability of expertise, as will be discussed later in the report. However, many questions remain and need to be addressed, and will be the focus of this report as outlined below.[4]

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[4] For more information, see Appendix A: Statement of Task.

- What are the characteristics of nuclear and radiochemistry experts? (Chapter 2)
- What is the current and future supply of and demand for nuclear and radiochemistry expertise (summarized in Chapter 8)—
    - in general? (Chapter 2)
    - in academic basic research and education? (Chapter 3)
    - in nuclear medicine? (Chapter 4)
    - in nuclear energy and power generation? (Chapter 5)
    - in nuclear security? (Chapter 6)
    - in environmental management? (Chapter 7)
- What is being done to ensure the supply of U.S. nuclear and radiochemistry expertise, and what are the ways to sustain or increase this supply in the future? (Chapter 9)

Chapters 1, 2, 3, 8, and 9 look at nuclear and radiochemistry expertise more broadly than Chapters 4 through 7, which provide more detailed assessments of specific nuclear and radiochemistry application areas. Each chapter ends with findings, which are the basis of the committee's overall recommendations presented in Chapter 10.

This report answers these questions by building on past efforts to assess needs in nuclear and radiochemistry and nuclear science and engineering more broadly, and by providing new insights on the unique needs and trends for nuclear and radiochemistry.

To accomplish its task, the committee collected new information from guest speakers (Appendix C), databases, websites, and other published information sources to determine current and likely future supplies of nuclear and radiochemistry experts. The committee surveyed members of professional organizations serving the nuclear/radiochemistry community to determine the demand for experts, and contacted representatives of industry, the national laboratories, and universities. Based on analysis of the resulting information, the committee formulated steps to be taken now and in the future to ensure a sustainable supply of U.S. nuclear and radiochemistry expertise.

NOTE ABOUT DATA COLLECTION FOR THIS STUDY

The committee found the objectives outlined in the statement of task difficult to meet for a number of reasons that are highlighted in this chapter and throughout the report. The members therefore had to seek alternate sources of information and extrapolate from limited data to understand employment supply and demand for expertise in this discipline. In summary, three major data limitations shaped the committee's work in this study:

1. **Employment classification**: Because nuclear and radiochemists are not classified by the SOC, the Bureau of Labor Statistics does not track employment or make projections in these areas. They are treated as a part of the broader occupation of chemists, nuclear technicians, nuclear medicine technologists, or nuclear power plant operators.
2. **Licenses or certifications**: There are no licenses or certifications required for nuclear and radiochemists, and ACS accreditation of chemistry departments does not have any specific provisions for nuclear chemistry content. As a result, the occupation is defined differently in different sectors and application areas. For the most part, nuclear and radiochemists are self-identified.
3. **Degrees**: Educational degrees are not specifically granted in nuclear and radiochemistry at the bachelor's or master's level. Ph.D.s in nuclear chemistry were captured by the SED in the past, but NSF removed the category from its questionnaire in 2004. The Survey of Doctorate Recipients (SDR) is not useful because it is a sample survey of current Ph.D.s, and the number of nuclear chemists (if they can be identified) is too small for meaningful analysis. The Higher Education General Information Survey (HEGIS) and the Integrated Postsecondary Education Data System (IPEDS) conducted by the Department of Education's National Center for Education Statistics (NCES) are not helpful because there is no designation for nuclear and radiochemistry in the Classification of Instructional Program (CIP) values on which the surveys are based.

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2

Defining Nuclear and Radiochemistry Expertise

The task of the committee was to examine demand for nuclear and radiochemistry expertise in the United States compared with the production (supply) of experts and to evaluate approaches for ensuring adequate availability of such expertise, including necessary science and technology training platforms for the next 20 years.[1] In this chapter, the committee describes characteristics of nuclear chemistry and radiochemistry experts and how they have changed over time, assesses the level of research activity in nuclear and radiochemistry (indicating the health of the discipline for attracting students), and assesses supply and demand for expertise in this area. Detailed analyses in the areas of academic research, nuclear medicine, energy, environmental management, and security are provided in Chapters 4 through 7, respectively.

As pointed out in Chapter 1, because nuclear and radiochemistry is not a single distinct occupational category, area of certification, or disciplinary field, the lack of readily or consistently identifiable data presented challenges to analysis. The committee explains its thought process and methods to overcome these challenges in meeting its charge.

CHARACTERISTICS OF NUCLEAR AND RADIOCHEMISTRY EXPERTS

Fundamentally, nuclear and radiochemists are chemists who hold one or more degrees in chemistry and have taken additional specialized courses and conducted laboratory work in nuclear and radiochemistry, including the study of radioactive nuclei, nuclear processes, and nuclear applications in which chemical behavior is important. Their research interests reflect the breadth of the discipline's applications—from nuclear energy to medical imaging, environmental chemistry, and nuclear security. They typically work in an organization's chemistry department or division. Many

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[1] The committee's complete Statement of Task is in Appendix A.

individuals who self-identify as nuclear and radiochemists are members of the American Chemical Society's (ACS's) Division of Nuclear Chemistry and Technology (DNCT), which is one of the 33 ACS specialty divisions. The committee considers this group to best represent, albeit not perfectly, the core of nuclear and radiochemistry experts.

Demographic and Publication Data

Demographic data for the DNCT membership provide some insights about the characteristics of nuclear and radiochemists and where they work. As of November 30, 2011, the DNCT (a.k.a. NUCL) had 1,015 members, mostly in the United States, about one quarter of whom are graduate and undergraduate students. Of the 78 percent of members who provided employment information, nearly half are in academic institutions, with the other half split between the government and the private sector (Kinard ACS, personal communication, February 22, 2011). ACS membership totals more than 164,000.

To get a sense of the professional affiliations of nuclear and radiochemists, the committee analyzed the e-mail addresses of U.S.-based authors of papers in three journals devoted to nuclear and radiochemistry research for 2006-2010 (Table 2-1). A significant fraction of articles in the journals were by government authors, especially for the *Journal of Radioanalytical and Nuclear Chemistry*.

Educational Background

The committee obtained educational information about nuclear and radiochemists from the DNCT website, which has in recent years served as a hub for tracking active nuclear and radiochemistry graduate programs as well as graduates of the Nuclear Chemistry Summer Schools. Starting from a list of 49 U.S. faculty member names last updated in 2008 (ACS 2008), the committee determined the thesis year and subject category for each faculty member using the ProQuest Dissertations and Theses (PQDT) database.[2] The committee then identified 242 advisees of those faculty members, also using PQDT, and determined the subject term for each thesis. The committee considers the advisees of the 49 faculty members to be nuclear and radiochemists given that the advisees would have likely taken advanced coursework and conducted research in nuclear and radiochemistry during their graduate careers.

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[2] See Table E-1 in Appendix E for a full list of faculty names, institutions, and thesis terms.

TABLE 2-1 U.S. Share of Articles in Three Nuclear and Radiochemistry–Related Journals, 2006–2010

	Total number of articles	Total U.S. articles	E-mail address ending of corresponding author			
			.gov	.edu	.com	Other*
Radiochimica Acta	567	74	28	28	2	16
Journal of Radioanalytical and Nuclear Chemistry	2,294	393	198	114	39	42
Radiation Measurements	1,539	181	29	55	25	72

* includes: .org, .net, and others.
SOURCE: Committee-generated search of Web of Science database (Thomson Reuters).

TABLE 2-2 Count of Published Theses of U.S. Nuclear and Radiochemistry Faculty Advisors and their Advisees According to Subject Terms Identified through the ProQuest Dissertations and Theses Database

Thesis Subject Term	Advisors	Advisees
With nuclear chemistry and other subject term(s)	7	87
Nuclear chemistry only	21	31
Without nuclear chemistry	21	111
TOTAL	49	229

SOURCE: Committee-generated table from data obtained through the ProQuest Dissertations and Theses database. For more information, see Table E-1.

A comparison of the subject terms on the published theses of both advisors and advisees is shown in Table 2-2. What stands out in these data is that many of the advisors listed research areas and thesis subjects other than nuclear chemistry on their theses, as did their advisees, and the proportions for each group are quite different: nuclear chemistry was chosen much less often by the advisees. From these data, the committee concluded that the self-identification of nuclear and radiochemists varies and has changed over time, and that simply following the numbers of nuclear chemistry Ph.D.s reported by the National Science Foundation (NSF) Survey of Earned Doctorates (SED) through 2003 provides an incomplete picture of the numbers of experts in this subfield of chemistry.

Both the SED and PQDT data thus likely present an undercount of available nuclear experts in the field because Ph.D. researchers come from a wide range of backgrounds and do not always label their work as "nuclear chemistry." For example, two committee members, Carolyn Anderson and Sue Clark, were identified in the DNCT faculty list (Appendix E; ACS 2008). Both are academic faculty members in nuclear and radiochemistry, but they have contrasting thesis subject terms: Anderson chose chemistry, analytical chemistry, and nuclear chemistry, while Clark chose chemistry and environmental science—thus, Clark (and presumably her advisees) would not be among the theses counted by a "nuclear chemistry" subject term search. Nevertheless, the committee determined that a keyword search of "nuclear chemistry" in the PQDT database provides at least a baseline measure of the number of new Ph.D.s each year since 2003 to compare with the SED data.[3]

Once the committee performed its keyword search of the PQDT database for nuclear chemistry it compared the results to the number of Ph.D. degrees conferred in the field of nuclear chemistry according to the SED[4] (although in 2004 nuclear chemistry was eliminated as a subfield in SED because of the low number of degrees reported in prior years, as discussed in Chapter 1; NSF 2010). A graph of SED and PQDT data since 1970 is shown in Figure 2-1. The committee chose to look back to 1970 because the number of nuclear chemistry Ph.D.s peaked in 1971 according to the SED.

The SED and PQDT series show similar patterns, generally declining from 1970 to 2000. However, there is a divergence between the two starting in the 1980s. One reason for this divergence is the difference between how the field of study in the PQDT and SED databases can be searched and how nuclear and radiochemists self-report their degree specialties. Specifically, while both PQDT and SED allow respondents to choose primary and secondary subjects for their field of study, only PQDT enables a search of all thesis subject terms collected (i.e., searches do not distinguish between primary and secondary field of study). Thus, the PDQT data include theses with nuclear chemistry as either a primary or secondary subject, whereas the SED data provide only a count of nuclear chemistry as the primary subject.

Moreover, as illustrated by the data in Table 2-2, students appear to be taking greater advantage of the opportunity to report more than one field of study in the PQDT form, which may help to explain the growing discrepancy between the PQDT and SED. For 2005–2010, when the SED no longer reported nuclear chemistry as a subfield, the PQDT shows a large increase in the number of Ph.D.s (Figure 2-1): by 2010, there were five times as many nuclear chemistry theses as there were nuclear chemistry degrees in 2003 (when the SED last reported such degrees).

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[3] The thesis submission form asks the author to choose a primary subject category, with the option of suggesting two additional categories. Nuclear chemistry (code 0738) is listed under mathematical and physical sciences. For more information see ProQuest (2011).

[4] The SED is a record of the number of Ph.D.s in scientific and other specialties in the United States based on graduates self-reporting their field and subfield of study. It is administered annually to all Ph.D. degree recipients from U.S. institutions of higher education. It is conducted by the National Opinion Research Center (NORC 2011) and sponsored by the NSF and five other federal agencies; results are made available on the NSF website (www.nsf.gov/statistics/srvydoctorates/) [accessed June 30, 2012].

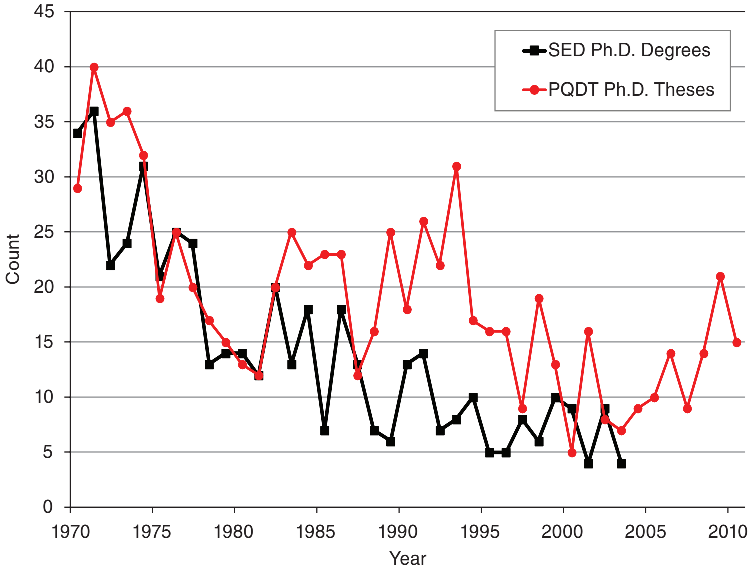

FIGURE 2-1 U.S.-granted Ph.D. degrees and dissertations in nuclear chemistry by year, 1970-2010, based on the National Science Foundation Survey of Earned Doctorates (SED) and the ProQuest Dissertation and Theses (PQDT) database. SED data (black squares) are based on selection of the term "nuclear chemistry" as the subfield of study on the questionnaire that was given to Ph.D. recipients for that year. PQDT data (red circles) are based on selection of the term "nuclear chemistry" as the subject area on the dissertation publication submission form.
SOURCE: NSF 2010; ProQuest 2011.

A similar recent growth in numbers of degrees has also been noted for nuclear engineering, based on a survey conducted by Oak Ridge Institute for Science and Education (Service 2011). Figure 2-2 shows the numbers of Ph.D. degrees in nuclear engineering generally declining since 1970, but with a significant increase since 2006.

Another characteristic important for nuclear chemistry and radiochemistry expertise is citizenship, due to the secure nature of much of the work in this field. Indeed, about 70 to 80 percent of nuclear chemistry Ph.D. degrees have been awarded to U.S. citizens,[5] in contrast to chemistry as a whole, in which 50 percent of Ph.D. degrees went to U.S. citizens in 2006

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[5] Calculated from the restricted use version of the NSF Survey of Earned Doctorates. The use of NSF data does not imply NSF endorsement of the research methods or conclusions contained in this report.

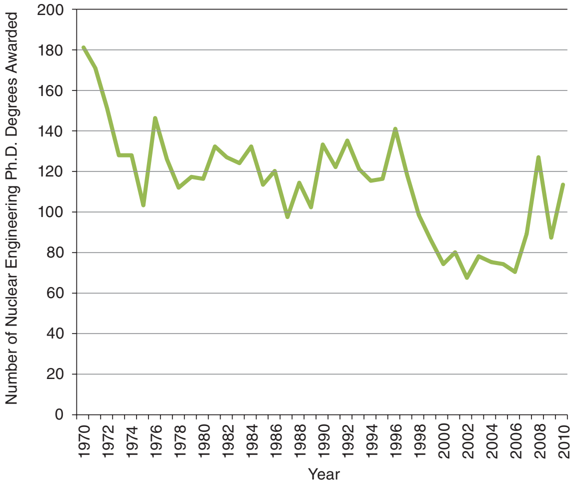

FIGURE 2-2 Trend in nuclear engineering Ph.D. degrees, 1970-2010.
NOTE: Includes programs with nuclear engineering majors and option programs in nuclear engineering equivalent to a major.
SOURCE: Jane Price, Oak Ridge Institute for Science and Education, Nuclear Engineering Academic Programs, personal communication, October 2011. (Also see Service 2011.)

(down from 85 percent in 1968; NSF 2011). Thus, drawing nuclear chemistry and radiochemistry expertise from the larger pool of chemistry degree recipients is challenged by the declining number of U.S. citizens earning Ph.D.s in chemistry.

RESEARCH ACTIVITY OF NUCLEAR AND RADIOCHEMISTS

Another measure of available expertise in nuclear and radiochemistry is the type of research activity, determined by keywords, reported in journals. The committee used the Web of Science database to search articles in scientific journals[6] in order to determine both the number of articles in the field of nuclear and radiochemistry and the number of articles with an author located in the United States. The search was based on the keywords uranium, plutonium, technetium, fluorine-18 (used in PET imaging), and thorium, which were chosen to capture a sample of nuclear chemistry research across application areas. The committee acknowledges that the search does

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[6] The committee used Web of Science rather than other search engines such as Scopus because Web of Science identifies country of author.

not provide a comprehensive analysis of nuclear chemistry research and likely represents an undercount of the number of publications in this field.

Figure 2-3 shows that the *number* of articles by authors in the United States generally rose from the 1990s through 2010, whereas Figure 2-4 shows that the *share* of articles from U.S. authors for these keywords has gradually decreased since the early 1970s. However, this trend has been noted recently for U.S. articles in all science and engineering fields (Table 2-3) (NSB 2010, Tables 5-25, all S&E, and 5-29, chemistry), suggesting that the decreasing share of U.S. articles is not an indication that the United States is falling behind but rather that other countries are catching up.

The generally rising number of articles since the 1980s indicates that the field of nuclear chemistry remains active and expertise is available, despite decreases in the number of faculty and students during this same time period (Figure 2-1). The discussions and data in Chapters 3–7 show that researchers are pursuing many exciting topics in nuclear and radiochemistry.

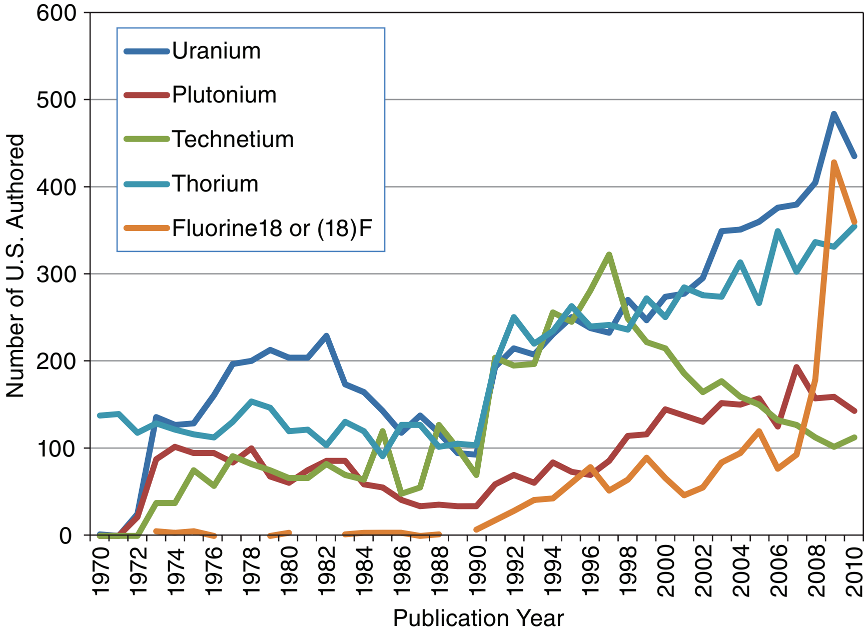

FIGURE 2-3 Number of U.S.-authored papers for selected nuclear and radiochemistry–related keywords, 1970-2010.
SOURCE: Web of Science keyword search, http://apps.webofknowledge.com, September 2011.

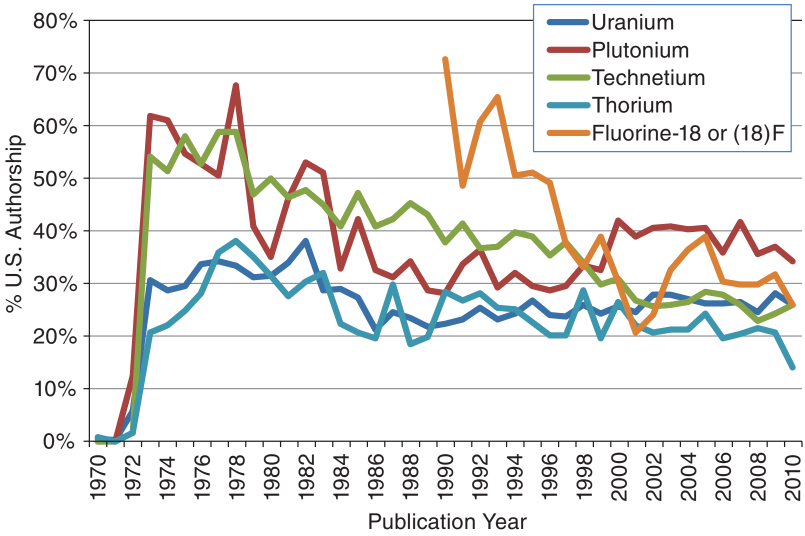

FIGURE 2-4 Percentage of U.S.-authored papers out of the total number of papers for selected keywords, 1970-2010.
SOURCE: Web of Science keyword search, http://apps.webofknowledge.com, September 2011.

TABLE 2-3 U.S.-Authored Articles for All Keyword Searches Related to Science and Engineering, Chemistry, and Nuclear and Radiochemistry

	1995			2009		
	Total Articles	U.S.-Authored	% U.S.-Authored	Total Articles	U.S.-Authored	% U.S.-authored
Subject areas						
All science and engineering	564,645	193,337	34%	788,347	208,600	26%
Chemistry	68,319	14,738	22%	102,825	16,430	16%
Nuclear and radiochemistry–relevant keywords						
Uranium	936	252	27%	1,717	485	28%
Plutonium	250	74	30%	432	160	37%
Technetium	628	245	39%	422	103	24%
Fluorine-18	184	88	48%	785	231	29%
Thorium	264	60	23%	332	69	21%

SOURCES: Subject areas: NSB 2012, Appendix Tables 5-27 (all S&E) and 5-31 (chemistry); keyword search of Thomson Reuters Web of Science, 2011; same as shown in Figures 2-3 and 2-4.

FUTURE SUPPLY AND DEMAND FOR NUCLEAR AND RADIOCHEMISTRY EXPERTISE

There are many uncertainties about what the demand will be for expertise in nuclear chemistry and radiochemistry over the next 20 years. For example, the areas of medicine and energy are driven significantly by commercial interests (as will be discussed in Chapters 4 and 5 respectively), while security and environmental management are driven more by government interests (Chapters 6 and 7, respectively).

As this committee was forming, there was a lot of discussion in the press about a possible nuclear renaissance that would expand development and use of nuclear energy around the world, which would in turn mean an increase in the need for skilled workers (many with nuclear chemistry and radiochemistry expertise). However, just days before the committee held its first meeting (March 16-17, 2011), the earthquake and tsunami hit Japan, severely damaging the Fukushima Daiichi nuclear power plant and surrounding areas and pretty much eliminating any plans for a nuclear renaissance in the United States in the near future. In the chapters that follow, the committee considers such scenarios and how they might affect future needs for nuclear chemistry and radiochemistry expertise.

Reports indicate that a sizable percentage of the nation's experts in nuclear and radiochemistry at national laboratories and universities is nearing retirement (APS 2008, 2010; DSB 2008; Graham et al. 2008; Stimson 2009). For example, data collected from national laboratories by this committee (see Appendix F for description) show that there are currently about 1,000 career employees with nuclear and radiochemistry related skills, about 10% of whom are at or nearing retirement age (60+ years), and more than half of these have a Ph.D. (Figure 2-5).[7] The projected demand for Ph.D.-level nuclear and radiochemistry experts (i.e., those with nuclear and radiochemistry degrees and those in jobs that involve nuclear and radiochemistry) at the national laboratories is estimated to be about 228 over the next 5 years (Table 2-4)[8]—almost 50 percent of the current total of Ph.D.'s.

In addition to needs at the national laboratories, another key factor that drives the demand for Ph.D.-level expertise—but is difficult to forecast—is research funding by the federal government, which translates into positions

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[7] Based on compilation of data obtained through personal communication from nine national laboratories: Argonne, Brookhaven, Idaho, Lawrence Berkeley, Lawrence Livermore, Los Alamos, Oak Ridge, Pacific Northwest, and Savannah River.

[8] Based on compilation of data obtained through personal communication from seven national laboratories: Brookhaven, Idaho, Los Alamos, Pacific Northwest, Lawrence Livermore, Oak Ridge, Pacific Northwest, and Savannah River.

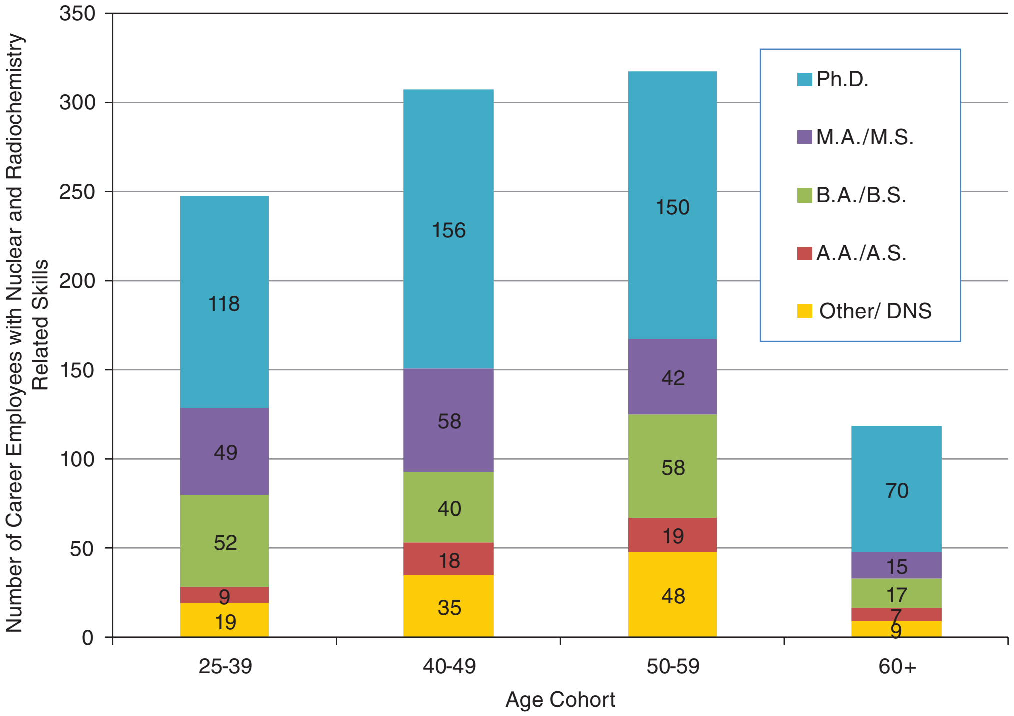

FIGURE 2-5 Estimated current number of national laboratory career employees with nuclear and radiochemistry–related skills according to degree.
NOTE: It is possible that the numbers presented here include a number of workers more closely related with fields other than nuclear and radiochemistry (e.g., nuclear physics and nuclear engineering).
SOURCE: Committee's compilation of data from nine national laboratories: Argonne, Brookhaven, Idaho, Lawrence Berkeley, Lawrence Livermore, Los Alamos, Oak Ridge, Pacific Northwest, and Savannah River.

in government laboratories and at universities, including the training of new Ph.D.s and postdocs. One significant source of basic research funding specifically for nuclear and radiochemistry is the Heavy Element Chemistry program in DOE's Office of Science, which has a favorable outlook in the near term (Table 2-5). DOE funding is also provided by the National Nuclear Security Administration (NNSA) and the Biological and Environmental Research, Nuclear Energy, Nuclear Physics, and Environmental Management program offices.

In addition, the Department of Homeland Security, National Institutes of Health, and National Science Foundation provide funding for nuclear and radiochemistry research. However, it is difficult to determine funding

TABLE 2-4 Projected Demand for Nuclear and Radiochemistry Expertise at National Laboratories

	Other/ DNS	A.A./A.S.	B.A./B.S.	M.A./M.S.	Ph.D.
1 year	3	3	12	7	35
2-5 years	32	17	58	52	193
Total	35	20	70	59	228

NOTES: Numbers based on projected terminations that will need to be replaced. It is possible that these numbers include a number of workers more closely related with fields other than nuclear and radiochemistry (e.g., nuclear physics and nuclear engineering).
SOURCE: Committee's compilation of data obtained through personal communication from seven national laboratories: Brookhaven, Idaho, Lawrence Berkeley, Los Alamos, Oak Ridge, Pacific Northwest, and Savannah River. See Appendix F for details.

TABLE 2-5 Funding Provided by the Heavy Element Chemistry Program in the Department of Energy's Office of Science (thousands of dollars)

FY 2005	FY 2006	FY 2007	FY 2008	FY 2009[a]	FY 2010[b]	FY 2011[c]
$10,506	$9,421	$9,427	$9,002	$11,033	$12,152	$15,107

[a] Omnibus.
[b] Appropriations.
[c] Continuing Resolution.
SOURCE: Philip Wilk, DOE, personal communication, November 4, 2011.

levels specific to nuclear and radiochemistry in the budgets for the other programs and agencies. A detailed listing of funding programs is discussed in Chapter 9.

FINDINGS

The identity of nuclear and radiochemistry experts varies and has changed over the past 20 years, as indicated by the committee's survey of published thesis subject areas, the subjects of journal publications (as assessed by keywords), and the age and sector demographics of membership in the DNCT. They may identify their expertise as environmental science, analytical chemistry, medicine, or other areas rather than nuclear and radiochemistry.

As discussed in this chapter, the number of nuclear chemistry–related Ph.D.s theses has stabilized or increased slightly since 2004, as is also true of the related discipline of nuclear engineering. This trend may be the result of federal investments in both research and education in recent years (see Chapter 9). However, it is not clear that an adequate supply of nuclear and radiochemistry experts will be maintained given increased demand (e.g., in sectors such as nuclear medicine and nuclear energy), possible shifts in public acceptance of nuclear energy, and the uncertainty that current funding levels will continue. Further, the diversity in educational backgrounds of nuclear and radiochemists, where and when they receive their training, and changes in how they identify their scientific specialties all make the accurate tracking of supply very challenging.

The next chapters explore the different subareas that require nuclear and radiochemistry expertise, and a summary of supply and demand data is presented in Chapter 8.

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3

Academic Basic Research and Education

The U.S. government has important missions that require technical innovation and scientific expertise that are applicable to national and global security, energy security, environmental stewardship, and human health (as discussed in several chapters of this report). Those missions are typically focused and applied, yet they are accomplished on a foundation of basic research and human development, principally executed in the academic community and related basic research institutions. The academic environment is typically well-suited for long-term research investigations, and is capable of focusing on the longer-term time horizons that are difficult—if not impossible—to accomplish in applied programs. This perspective is especially important for developing graduate research efforts that educate new staff to a depth of expertise unattainable in other venues, and a significant fraction of the basic research funding that goes into academia goes to support these students.

Basic research in the nuclear and radiochemistry field supports the numerous and varied applications of the discipline. For example, a list of 14 grand challenges identified by a committee of the National Academy of Engineering in 2008 (NAE 2008) included at least four challenges that directly involve nuclear chemistry:

- Provide Energy from Fusion;
- Reverse Engineer the Brain;
- Prevent Nuclear Terror (forensics, aftermath, and cleanup); and
- Engineer the Tools of Scientific Discovery (particularly space-based systems).

RESEARCH OPPORTUNITIES

An illustrative list of the types of applied needs that would benefit from basic research in the academic environment by major programs is given below.

Nuclear Medicine and Radiotracer Applications

- New diagnostic tools are needed that include both novel radiopharmaceuticals and new applications of nuclear monitoring techniques. Examples that have recently expanded medical frontiers include Positron Emission Tomography (PET) *in vivo* imaging (example shown in Figure 3-1) and Accelerator Mass Spectrometry (AMS) that can bring attomole sensitivity to pharmacokinetic measurements within a patient.
- New radioisotopes and radiopharmaceuticals for therapeutic applications in cancer research are needed that will allow more specific targeting of individual cancer cells when combined with next-generation drug delivery systems.
- Alternative methods for producing and separating radioisotopes that have potential medical applications are needed, such as those produced with new accelerator systems, or from harvesting reactor produced elements.

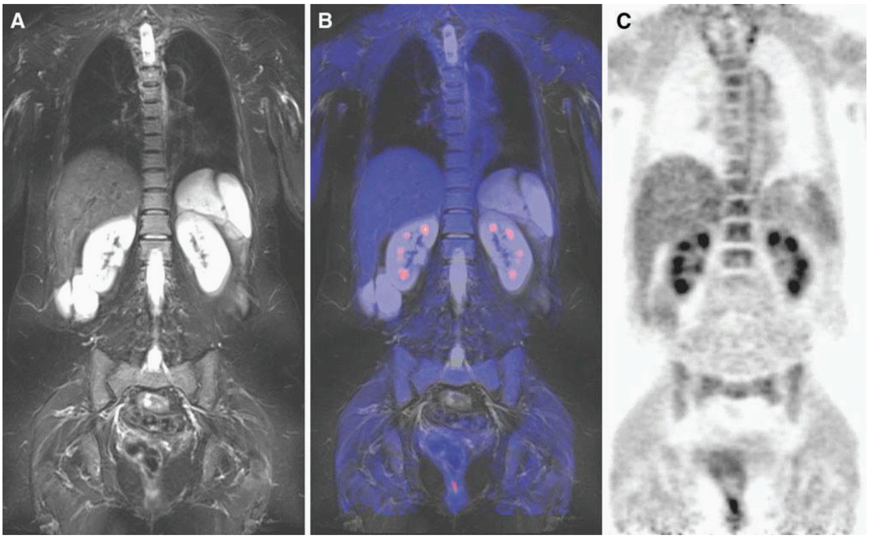

FIGURE 3-1 A typical FDG-MR/PET image in coronal view. Magnetic resonance/Positron Emission Tomography (MR/PET) imaging of a 53-year-old female patient with suspicion for tumor recurrence of cervix cancer. (A) coronal T2 weighted inversion recovery sequence (STIR). (B) corresponding superimposition. (C) F-18 fluorodeoxyglucose (FDG) PET acquired with the whole-body MR/PET system (three bed positions, 6 min per bed, 120 min post injection of 361 MBq (9.8 mCi) FDG).
SOURCE: Schwenzer et al. 2012.

- Nuclear imaging provides critical information about the potential viability of new pharmaceuticals early in the course of drug development. Preclinical information about the pharmacokinetics and early pharmacodynamic behavior of the pharmaceutical is used to determine the advancement of the new drug into human clinical trials. Likewise imaging studies conducted in parallel with the clinical phases of drug development may assist in making the important go/no-go decisions that will save time, cost, and effort.
- New nanoparticles and nanomaterials are being explored as carriers for medical imaging contrast agents and the targeted delivery of therapeutics. The pharmacokinetics and potential toxicity of these materials is largely unknown. Nuclear imaging techniques may be employed to evaluate the distribution and fate of these new materials in preclinical and clinical research studies on the microdose scale.
- Energy production from biomass, biofuels, is a rapidly emerging area of alternative energy research. Radiotracers are being used to map the enzymatic pathways involved with synthetic fuel production.

Homeland Security

- Additional nuclear forensics techniques are needed that will allow for rapid and more precise post-detonation detection and source attribution with microscopic samples that are often widely dispersed geographically.
- Novel methods to detect illicit transport of radioactive materials on a global scale need to be developed as well as sophisticated remote detection of nuclear activities.

Weapons

- There is a need to develop and to interpret radiochemical signatures to accurately analyze performance and maintain reliability when direct experiments are no longer possible.
- New initiatives are needed to obtain the basic nuclear data necessary to reduce uncertainty in extremely complex models of what occurs on very short timescales in high-energy environments, for example as the weapon is exploding, or the impact of the explosion on the atmosphere, planet surface, etc.

Non-proliferation and Arms Control

- An expanded collaboration with the International Atomic Energy Agency is needed to design and conduct global environmental sampling for compliance verification and treaty-monitoring activities.
- Additional nuclear forensics signatures need to be developed for non-proliferation efforts worldwide.

Nuclear Power

- Next generation actinide-based fuels will need new chemical separations methods to provide the future fuels for society's energy demands.
- Significant nuclear and radiochemistry and materials science issues with nuclear fuel under extreme conditions need to be resolved as a function of fuel burn-up. This includes both experimental methods development as well as significant theoretical development in f-shell element modeling.
- Fuel recycling and reprocessing will require new and improved advanced separations technologies in complex environments, especially with respect to actinide elements (example shown in Figure 3-2).

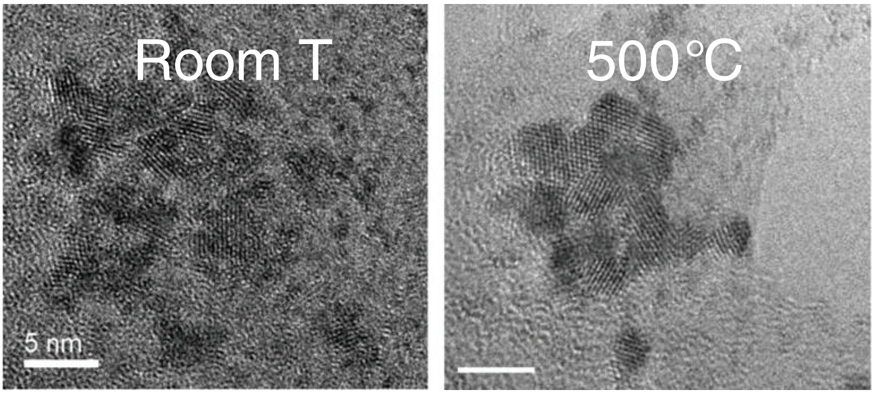

FIGURE 3-2 Thermal stability and sintering behavior of the uranium oxide (UO_2) nanoparticles studied utilizing transmission electron microscopy (TEM) with an in situ heating stage. These UO_2 nanoparticles exhibit sintering temperatures in the range of 500°C–600°C, which is between 700–1000°C lower than reported bulk UO_2 sintering temperatures.
SOURCE: Nenoff et al. 2011.

- The national need for waste processing and long-term disposal needs to be addressed, especially with respect to radioisotope fate and transport in the environment.

Environmental Remediation and Management

- There is a mostly untapped potential for novel isotopic methods for environmental monitoring that needs to be developed. This is strongly connected to both theoretical and experimental studies of radioisotope sequestration and fate and transport within the environment and can include topics as diverse as the modality of energy dissipation in materials or the improvement of detection limits for large-area sampling methods.
- Novel separation technologies need to be developed as part of long-term remediation strategies, especially for long-lived radionuclide fission products and actinides (example shown in Figure 3-3).

Clearly much of the research in nuclear and radiochemistry is of national importance, but for the most part it is not funded significantly by the private sector. Although public-private partnerships are certainly possible in areas of nuclear power and medicine, the bulk of the nuclear and radiochemical research and development must be supported by the federal government if these applications of nuclear and radiochemistry are to continue—or in the case of environmental management, because they have already occurred extensively in this country and elsewhere. Nuclear and radiochemistry has also become a mature research field over the past 50 years or so, and while this short list of current and future research needs clearly indicates that there is significant fundamental research left to be conducted in this field, a good number of the exciting new developments lie at the interface of traditional nuclear and radiochemistry with other areas such as medicine, materials science, environmental science, and forensic science. Broadening the definitions of nuclear and radiochemistry to encompass and engage academic interests beyond traditional boundaries would in general infuse the discipline with new scientists that can help address personnel shortfalls. An example of networking interdisciplinary academic scientists in actinide research has occurred in Europe with the formation of ACTINET-I3, the Integrated Infrastructure Initiative for Actinide Science (ACTINET 2012).[1] This

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[1] The objective of the present European Commission Seventh Framework Program (FP7) Integrated Infrastructure Initiative (I3) ACTINET-I3 is to reinforce the networking of existing European infrastructures in actinide sciences, and to facilitate their efficient use by the European scientific community in order to keep a leading position in the field of nuclear energy. For more information see ACTINET 2012.

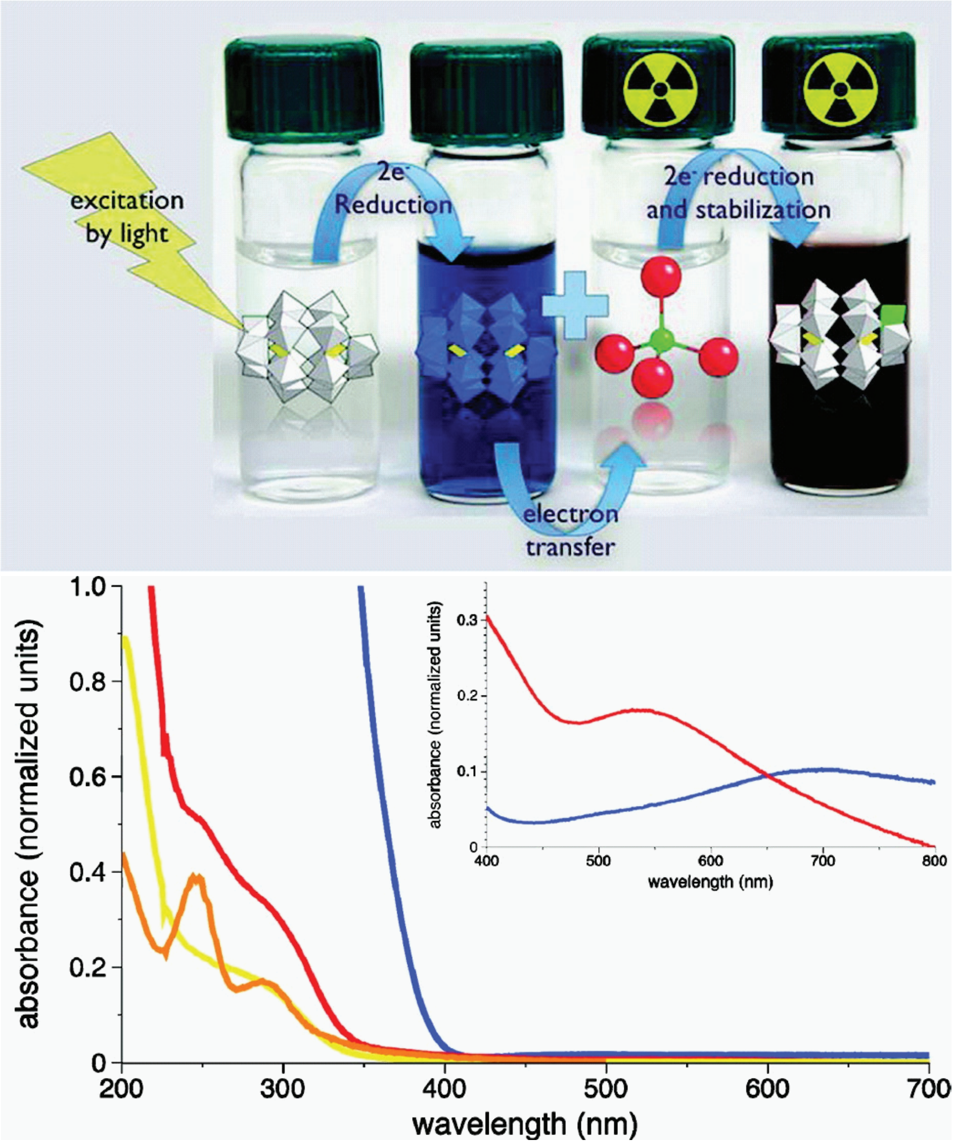

FIGURE 3-3 A new strategy for the reduction of $^{99}TcO_4^-$ and the chemical incorporation of the reduced ^{99}Tc into a metal oxide material. Color changes obtained during the photolytic reduction of $^{99}TcO_4^-$ using α_2-$[P_2W_{17}O_{61}]^{10-}$. Upon exposure to sunlight in the presence of 2-propanol, the clear colorless α_2-$[P_2W_{17}O_{61}]^{10-}$ (A, yellow trace) becomes reduced and exhibits the characteristic blue solution (B, blue trace). Upon addition of a clear colorless solution of $^{99}TcO_4^-$ (C, orange trace), the solution changes color from blue to dark orange (D; red trace).
SOURCE: Burton-Pye et al. 2011.

organization encompasses classical nuclear and radiochemistry disciplines, but also includes research scientists working in closely related fields that are impacted by nuclear and radiochemistry.

NUCLEAR AND RADIOCHEMISTRY ACADEMIC PROGRAMS

Academic research programs in nuclear and radiochemistry have traditionally been found within chemistry departments in the university setting. They are typically at the program level (individual faculty research groups); these programs are not distinct efforts from their home departments. There are exceptions, for example, the nuclear chemistry efforts at the University of Texas, Austin are located within the Nuclear Engineering Program in the Department of Mechanical Engineering (University of Texas 2011). There are other engineering programs such as the biomedical engineering program at the University of California, Davis that offers courses that teach radiochemistry as applied to nuclear medicine imaging (UC Davis 2011). These niches have often been established to locally optimize around funding streams or critical research facilities. These academic research programs provide a critical role in graduate-level education for those who will become future faculty members in academia and staff at national laboratories, as well as undergraduate education for the bulk of the nuclear and radiochemistry scientific workforce, which is especially important for industries such as nuclear energy, nuclear medicine, and environmental monitoring.

At the start of this study, there was no comprehensive up-to-date listing of nuclear and radiochemistry academic research programs. Thus, the committee had to collect information on the current status of the academic research and education components of nuclear and radiochemistry in the United States.

Faculty Members

The committee once again looked to a list of faculty compiled by the American Chemical Society (ACS) Division of Nuclear Chemistry and Technology (DNCT) as a starting point (ACS 2008). The DNCT list of nuclear and radiochemistry graduate programs can be found on its website, and is based on the ACS Directory of Graduate Research (DGR) listing of graduate chemistry programs (mainly in the United States) and DNCT membership. The committee then used the online version of DGR (DGRWeb; ACS 2009) to determine year of birth and age of faculty, and to verify faculty appointments for those on the 2008 DNCT list. Faculty appointments were also verified by checking department websites. Additional nuclear and radiochemistry faculty (not on the 2008 DNCT list) were identified using DGRWeb by searching the research area field, as well as by conducting a survey of chemistry department chairs (see Appendix H). From the compiled information (shown in Figure 3-4), the committee observed that the number of faculty dropped from 72 in 1999 to 60 in 2005. There was also a decrease of 24 faculty from 2005 to 2011, but due to the addition of 26 new nuclear and radiochemistry faculty members at 22 universities, the number of faculty increased from 60 professors in 2005 to 62 in 2011.

Figure 3-5 shows faculty by year according to age for 1999-2009, and indicates that about half of faculty over this time range is at or is approaching retirement age (61 or older). However, the proportion of those who are 71 or older grew significantly.

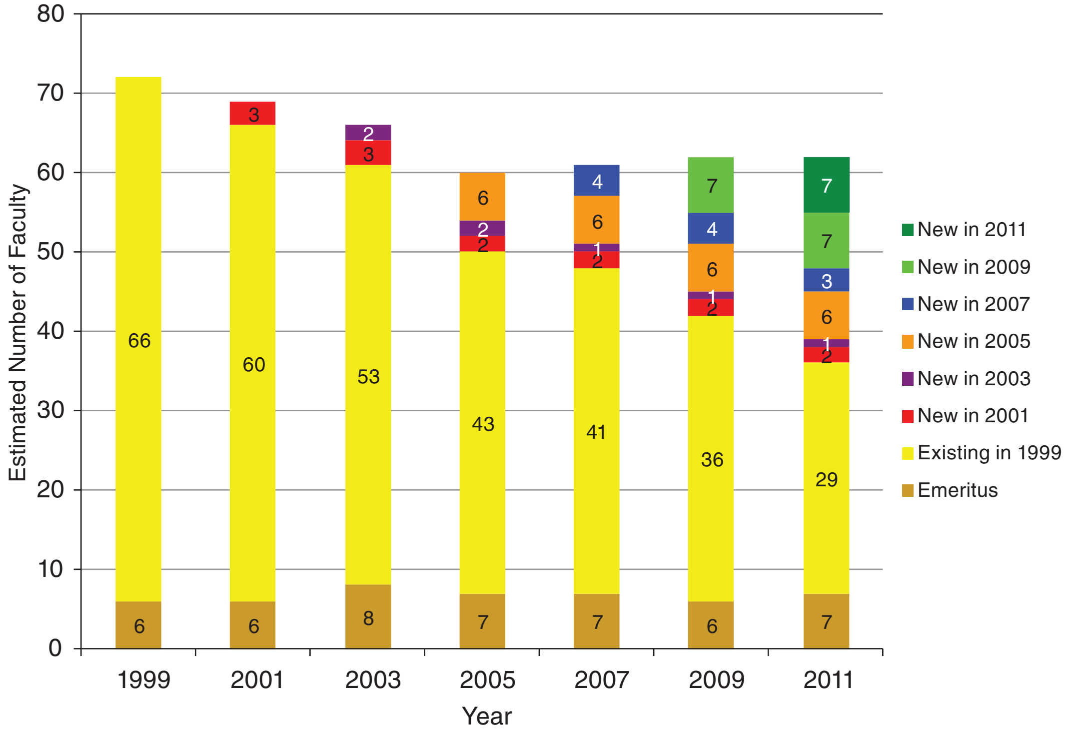

FIGURE 3-4 Total reported number of existing and new nuclear and radiochemistry faculty at U.S. graduate institutions.
SOURCE: DNCT listing (ACS 2008), ACS Directory of Graduate Research (ACS 2009), faculty websites, and survey of chemistry department chairs (see Appendix D and H).

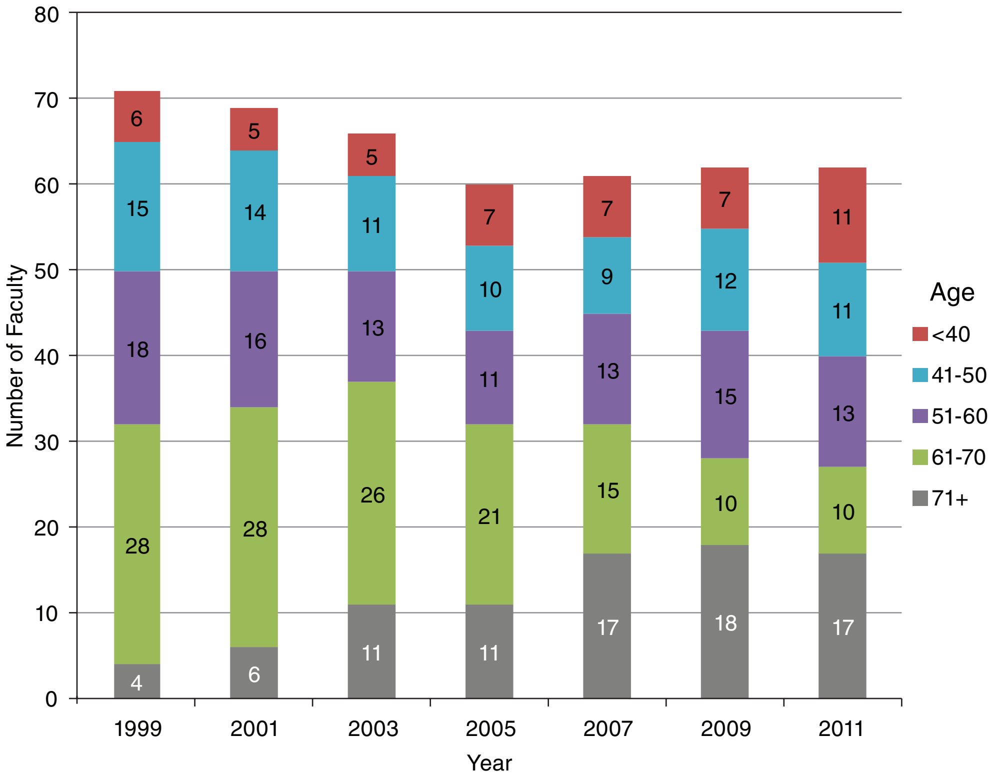

FIGURE 3-5 Total reported number of nuclear and radiochemistry faculty at U.S. institutions, by year and faculty age.
NOTE: Year of birth not available for all faculty, so yearly totals are slightly less than those shown in Figure 3-4.
SOURCE: Data from ACS 2008, 2009.

Doctoral Education

As noted in Chapter 2 of this report, a decline in nuclear and radiochemistry Ph.D. recipients had been observed for decades (1970-2000). However, ProQuest Dissertations and Theses (PQDT) data (Figure 2-1) suggests the decline may have reached a plateau or even a rise recently. There has also been a stabilization in the number of academic faculty—as indicated in the data above (Figures 3-4 and 3-5).

The committee gathered further information about faculty advisors identified on the 2008 DNCT list. According to that list, there are 20 U.S. graduate programs with at least one faculty member conducting research in the area of nuclear and radiochemistry (Table 3-1). Half of the universities in the list are members of the American Association of Universities (AAU), which are considered to be the leading research-intensive U.S. universities. The AAU members also account for about half of the total faculty members listed in the table. Out of the 20 graduate programs listed in Table 3-1, 13 have two or more faculty and are advising the majority of Ph.D. theses (91/114 or 79 percent). Again, half of those are from AAU member institutions. However, only three of the departments listed are ranked among the top 25 chemis-

TABLE 3-1 Number of Faculty Advisors and Ph.D. Theses They Advised for U.S. Nuclear Chemistry and Radiochemistry Graduate Programs Identified by ACS DNCT in 2008

University	Home Department	Number of Nuclear Chemistry Faculty in 2008**	Number of Nuclear Chemistry advisee Ph.D. theses completed 2000-2010
Auburn University	Department of Chemistry	2	11
Clemson University	Department of Environmental Engineering and Earth Sciences	3	6
Indiana University*	Department of Chemistry	1	3
Michigan State*	Department of Chemistry	3	13
Oregon State University	Department of Chemistry	2	1
Pittsburgh State University	Department of Physics	1	1
Stony Brook University—State University of New York*	Department of Chemistry	2	2
Tennessee Technological University	Department of Chemistry	2	2
Texas A&M University*	Department of Chemistry	3	7
University of Alabama	Department of Chemistry	1	4
University of California, Berkeley*	Department of Chemistry	4	13
University of Idaho	Department of Chemistry	1	10
University of Kentucky	Department of Chemistry	1	1
University of Maryland, College Park*	Department of Chemistry	1	7
University of Missouri-Columbia*	Department of Chemistry	3	6
University of Nevada-Las Vegas	Department of Chemistry–Radiochemistry	3	6
University of Rochester*	Department of Chemistry	1	0
University of Washington*	Department of Chemistry; Department of Radiology	2	1
Washington State University	Department of Chemistry	6	11
Washington University in St. Louis*	Department of Molecular Biology and Pharmacology; Department of Radiological Sciences	4	9
TOTAL		46	114

*Member AAU (American Association of Universities)
**Only includes faculty who advised Ph.D. theses for 2000-2010.
SOURCE: Data from ACS 2008, 2009, and ProQuest 2011.

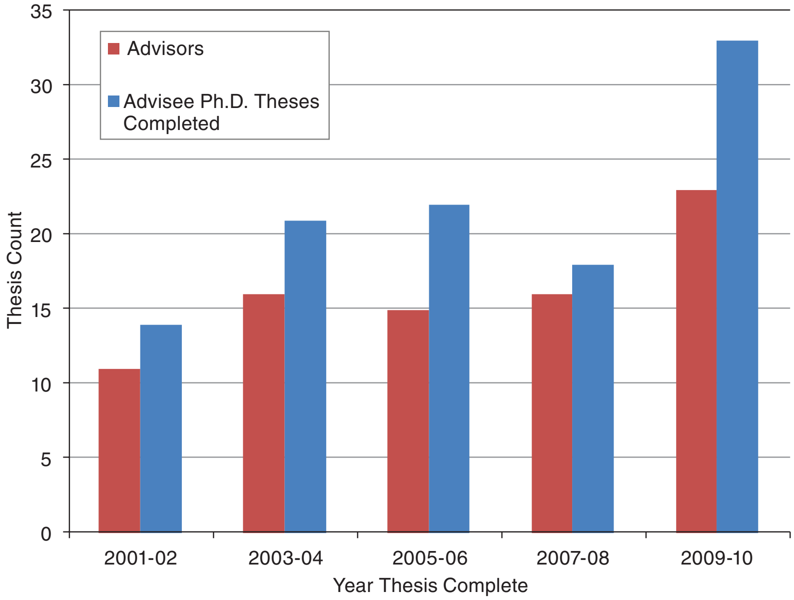

FIGURE 3-6 Count of nuclear and radiochemistry Ph.D. thesis advisors and corresponding advisee theses completed at U.S. institutions, by year, for faculty listed in Table 3-1. SOURCE: Based on faculty data from ACS 2008 and thesis advisor search (ProQuest 2011).

try departments (for determination of rankings, see NRC 2011). Figure 3-6 shows the number of nuclear and radiochemistry faculty advisors from the 2008 DNCT list and the number of advisee Ph.D. theses completed for those same advisors, which has clearly grown over the past decade.

Nuclear Chemistry and Radiochemistry Coursework

Another measure of nuclear and radiochemistry education in the United States as evidence for estimating the supply of expertise, is the number of institutions that offer specific coursework for undergraduates and graduates. In order to assess this number, the chairs of approximately 138 chemistry departments of graduate institutions (including the approximate top 100 according to National Research Council 2011 assessment of research-graduate programs [NRC 2011]; for a list of chairs and departments, see Appendix H) across the United States were contacted by e-mail and asked "Does your department offer courses which are devoted entirely or in part to nuclear and/or radiation chemistry?" Forty-four chairs responded to the survey and twelve replied yes.[2] This roughly corresponds with the departments listed in Table 3-1, with two or more nuclear and radiochemistry faculty. Eight respondents indicated their departments offer two courses, and only two respondents (Washington State University and Washington University at St. Louis) offer three or more courses. Course enrollment numbers ranged from 5 to 30. Only five courses offered included a laboratory component. Examples of course titles offered include:

- Nuclear and Radiochemistry Laboratory
- Radioactivity and its Applications
- Modern Nuclear Chemistry
- Nuclear Chemistry
- Nuclear and Radiochemistry
- Radiochemistry: Introduction to Inorganic Chemistry
- Radioactivity and Radiation Safety
- Selected Topics in Physical Chemistry II (Radiation Detectors)

An important aspect of offering focused courses in nuclear and radiochemistry is to provide students with content on actinide chemistry. The chemical behavior of elements with 5f orbitals and electrons (actinides) is an appropriate part of advanced inorganic chemistry. Because all isotopes of the actinides are radioactive, actinide chemistry is also an appropriate component of nuclear chemistry and radiochemistry courses and textbooks.

The committee also performed a web search to identify nuclear and radiochemistry programs and course offerings at the 25 top ranked chemistry departments (for determination of rankings, see NRC 2011). The results of the search are presented in Table 3-2. Six chemistry departments in the top 25 were found that offer courses in nuclear and radiochemistry, and only two also have faculty members conducting nuclear or radiochemistry research. This raises concerns, because if the maturation of the field means less involvement in nuclear and radiochemistry research from the top research schools, it will grow increasingly difficult to attract top students into the field.

Supply of Bachelor's and Master's Degrees

Given that there is no specific nuclear chemistry or radiochemistry undergraduate degree granted, it is difficult to determine the number of B.S.

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[2] This estimate (12/44 or 27.3% of programs) must be viewed with caution, given that only about 31.9% of departments responded and respondents were inconsistent with providing identifying information.

TABLE 3-2 Nuclear Chemistry Program Information Identified at Top 25 U.S. Chemistry Departments

School	Nuclear and Radiochemistry Program Information	Course Title
California Institute of Technology	One undergraduate course	CHEM127 Nuclear Chemistry
Pennsylvania State University	One graduate course	CHEM 406 (NUC E 405) Nuclear and Radiochemistry
Texas A&M University	Multiple active research faculty, three undergraduate courses	CHEM 102 Fundamentals of Chemistry II (first year program); CHEM 464 Nuclear Chemistry; CHEM 474 Experimental Nuclear and Radiochemistry
University of California, Berkeley	Multiple research faculty, two undergraduate courses, and one graduate course	CHEM 143 Nuclear Chemistry CHEM 146 Chemical Methods in Nuclear Technology CHEM 243 Advanced Nuclear Structure and Reactions
University of North Carolina, Chapel Hill	One undergraduate course	073 First-Year Seminar: From Atomic Bombs to Cancer Treatments: The Broad Scope of Nuclear Chemistry
University of Washington, Seattle	Two undergraduate courses	CHEM 410 Radiochemistry Laboratory CHEM 418 Nuclear Chemistry

SOURCE: Program information and course titles were identified by searching available department websites and university course listings. For determination of rankings, see NRC 2011.

level nuclear and radiochemists that might be available to supply expertise. However, it is possible to make a rough estimate based on those departments that are known to have nuclear and radiochemistry faculty and coursework (Table 3-1), and numbers for chemistry as a whole obtained from available survey data. Table 3-3 shows the number of chemistry bachelor's degrees awarded (NSF 2012) at 11 universities the committee identified as having two or more nuclear and radiochemistry faculty and course offerings. The data show that there was an average of 494 bachelor's degrees awarded per year for the past 5 years (2006-2010) for these universities. With a conservative estimate that 10 percent of the students would take an upper level course in nuclear and radiochemistry, there would be a supply of 49 B.S. level chemists with some background in nuclear and radiochemistry. That number of B.S.-level chemists roughly corresponds with the information about course enrollments from chemistry department chairs discussed earlier, which had a range of 5-50 students per course focused on nuclear and radiochemistry.

Degree data is also available for master's degrees (NSF 2012) at the same 11 universities listed in Table 3-3. It was determined that an average of 98 M.S. degrees were awarded per year at these universities over the

TABLE 3-3 Bachelor's Degrees in Chemistry Conferred for Universities with Nuclear and Radiochemistry Faculty and Coursework in Chemistry Departments, 2001-2010

University*	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Auburn University	8	9	7	4	7	11	16	17	9	12
Michigan State University	50	43	36	44	63	60	62	50	53	50
Oregon State University	10	10	19	21	27	34	34	30	26	32
Stony Brook University	19	2**	26	18	24	31	28	31	35	42
Tennessee Technological University	16	27	24	17	25	24	33	25	16	21
Texas A&M University	44	34	37	42	43	47	47	51	68	49
University of California Berkeley	74	64	71	60	89	100	147	147	147	106
University of Missouri Columbia	23	19	20	20	19	28	27	23	28	21
University of Nevada Las Vegas	13	8	9	7	8	49**	8	9	8	7
University of Washington Seattle Campus	39	56	66	63	86	89	101	112	112	103
Washington State University	13	8	14	6	13	12	12	9	10	13
Subtotal	309	280	329	302	404	485	515	504	512	456
TOTAL CHEMISTRY	9,822	9,448	9,332	9,305	9,937	10,891	11,255	11,825	12,131	12,321

*Universities from Table 3-1 with two or more nuclear and radiochemistry faculty in chemistry departments.

**All values are given as reported, but these two seemed inconsistent with values for the series. They may be the result of institutional changes in reporting.

SOURCE: Department of Education, National Center for Education Statistics, Integrated Postsecondary Education Data System (IPEDS) completion survey for National Science Foundation population survey specific academic institutions, by level of degree and detailed standardized academic discipline (NSF 2012).

past 5 years (2006-2010). Again, with a rough estimate that 10 percent of the students at these universities would take coursework or be involved in nuclear and radiochemistry research, there would roughly be a supply of 10 M.S level chemists per year.

Current Educational Initiatives

Earlier reports have recommended efforts be undertaken to sustain academic programs in nuclear and radiochemistry.[3] One of the first initiatives to attract new undergraduate student interest in the field of nuclear and radiochemistry was the Summer School in Nuclear and Radiochemistry, supported by the U.S. Department of Energy. This program began in 1984, hosted in the Nuclear Science Facility at San José State University, and subsequently expanded to two concurrent offerings at San José State University and Brookhaven National Laboratory (Clark 2005; Kinard and Silber 2005; Peterson 1997). Data collected about the graduates of the summer schools indicate many of them go on to nuclear and radiochemistry related careers (See Box 9-1). Other early-stage academic pipeline initiatives in related areas have been established more recently, including a Nuclear Forensics Undergraduate Summer School; and are listed in Tables 9-2 and 9-3. All of the initiatives target students or young faculty with a goal of providing an introduction to nuclear or radiochemistry.

Constraining Factors and Barriers

Academic nuclear and radiochemistry programs—especially academic experimental research programs—face a number of factors that create costs, complexity, or other organizational challenges that affect decisions to enter or remain in this field. These factors hinder the ability to establish new programs and are often considered when university leaders are deciding whether to replace retiring nuclear and radiochemistry staff. Absent a clear perceived benefit to the university (specifically, for example, extramural research funds), the likelihood of starting a new program or sustaining an existing program is diminished.

Examples of factors that serve as constraints or barriers include:

- **Cost of experimental facilities for handling dispersible radionuclides.** This includes both initial capital costs and ongoing operations, regulatory, and maintenance costs.

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[3] See Chapter 1.

- **Regulatory complexity.** Associated issues including licensing, inspections, waste disposal, and liability language in research contracts. Particular trans-uranic elements such as plutonium may be very difficult to use in research outside of the national laboratory setting which argues strongly for close academic ties to the national labs.
- **The lack of long-term stability in funding opportunities.** In particular, this issue can have a dramatic effect on the attractiveness of an academic field to young students and faculty alike. If there is a perception that jobs and funding opportunities will not be available over the long term, then it is very difficult to convince students to enter the field. Without students entering the field and without competitive access to extramural research funds, nuclear and radiochemists are unlikely to compete favorably in the academic setting with other disciplines.
- **Lack of presence or mention in university curriculum.** Once the number of people trained in nuclear and radiochemistry drops below a critical mass, there is far less awareness of it as a potential field of interest for young students to pursue. Even more than the uncertainty of jobs in the field in the future, ignorance that the field even exists will drastically reduce the number of students entering the field. Since so few educational institutions even offer coursework in nuclear and radiochemistry, it is unlikely that a significant fraction of the academic population has even heard of the discipline in the context of current research opportunities and needs.

FINDINGS

The number of Ph.D.s and faculty members in nuclear and radiochemistry appears to have stabilized, but is still fragile. While, there had been a continuing decline in the number of nuclear and radiochemists in the United States since the 1970s, there is evidence that it has leveled off over the past 5 years:

- The number of theses with nuclear chemistry as a subject keyword grew from 5 in 2005 to 15 in 2010 (Figure 2-1).
- The total number of nuclear and radiochemistry faculty remained at around 60 from 2005 to 2011 (Figure 3-1).

As will be discussed in Chapter 9, this stabilization may be due to recent increases in funding opportunities aimed at academic pipeline issues.

Data sources for tracking nuclear and radiochemistry expertise are limited and sporadic. Many of the data sources typically used to assess workforce, such as the Survey of Earned Doctorates or Bureau of Labor Statistics Employment Outlook do not specifically track the nuclear and radiochemistry field. For years, the ACS DNCT has attempted to keep track of and make available information on educational opportunities in nuclear and radiochemistry, largely through the efforts of one person. Thus, there is no comprehensive and complete data source regarding nuclear and radiochemistry workforce from which to draw data on a routine basis. The lack of a consistent basis set of data makes it difficult to assess the effectiveness of various programs attempting to address academic pipeline issues, since it is harder to quantify, make comparisons, and interpret trends. Tracking the supply and demand of nuclear and radiochemists is a relatively low-cost endeavor that will be important for prudent investment of public funds and to assure that future significant gaps between the human resource supply and the job market are identified with sufficient advance notice to effect any needed changes.

There are currently few active graduate programs that have more than one nuclear chemist in the department. Out of over 100 chemistry graduate programs across the United States, only 13 have two or more active nuclear and radiochemistry faculty members (Table 3-1). At the same time, these institutions produced the majority of Ph.D.s in the field over the past 10 years (91/114 or 79 percent). This strongly suggests that programs that are centered upon a single nuclear or radiochemistry faculty member are unsustainable. Critical facility needs for nuclear and radiochemistry research and education are lost when university programs are lost through attrition. The costs to re-initiate a research facility at a new institution are much higher than maintaining or upgrading existing facilities, but neither will take place without sufficient critical mass of faculty to support the facility.

There is little or no nuclear and radiochemistry coursework being offered at U.S. universities. The committee identified only 12 chemistry departments that offer one or more courses developed entirely or in part to nuclear and radiochemistry. Only two offer three or more courses. In addition, the committee found that only five out of the top 25 ranked U.S. chemistry departments have nuclear and radiochemistry research and/or coursework.

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4

Medicine

INTRODUCTION

Nuclear medicine is a specialty that involves the use of radiopharmaceuticals (a radionuclide either by itself or attached to a molecule) in conjunction with highly specialized imaging instrumentation to detect the radionuclide emissions in the body after oral, inhalation, or intravenous administration. Radiopharmaceuticals may be used to assess normal physiologic processes, diagnose and treat diseases, measure the distribution of drugs, and monitor treatment effectiveness.

Fostered by unique partnerships between national laboratories, academia, and industry, the field of nuclear medicine has evolved over the past 55 years through advances in imaging instrumentation, radionuclide production, and radiopharmaceutical development. Nuclear reactors and particle accelerators have been developed to produce a wide array of radionuclides for diagnostic and therapeutic applications; innovative chemistry and automated synthesis devices have been designed to produce a multitude of new radiopharmaceuticals for imaging and treatment; and high-resolution and high-sensitivity instrumentation has been advanced for detection of radiopharmaceutical distributions in living systems, from small animal models to humans.

Radiochemistry is used in nuclear medicine to combine elemental radionuclides with biologically active chemical compounds to form radiopharmaceuticals. These agents are designed to trace specific metabolic or biologic pathways and localize to specific organs or sites of disease. Instruments with external detectors—such as gamma cameras, single photon emission computed tomography (SPECT), or positron emission tomography (PET) scanners—then produce an image of the distribution of radioactivity in the living system. Radiopharmaceuticals have been developed to study a wide range of normal processes and disease states, including normal brain function, aging, neurodegenerative diseases, cardiovascular disease, and cancer.

The field of nuclear medicine is highly diverse and multidisciplinary, but nuclear and radiochemistry are the core disciplines because radiopharmaceuticals are integral to every nuclear medicine study. The workforce for the field of nuclear medicine consists of personnel at all levels of education (B.S., M.S., Ph.D., Phar.M.D., and M.D.) in academia, industry, and government laboratories. In academia, nuclear and radiochemistry expertise involving nuclear medicine is mainly found in radiology departments, not in chemistry departments.

Those performing nuclear and radiochemistry in the field of nuclear medicine are trained in a wide variety of disciplines and may receive on-the-job training. The field of nuclear medicine is growing rapidly, and properly trained workers will be essential for continued success in this important area of modern health care.

A BRIEF HISTORY OF RADIOPHARMACEUTICAL DEVELOPMENT[1]

The use of radioactivity in medicine started with Wilhelm Röntgen, who discovered x-rays in 1895. A week after his discovery, Röntgen took an x-ray of his wife's hand, clearly revealing her wedding ring and bones. In 1901 he was awarded the Nobel Prize in Physics for his innovation.

In 1934, building on the work of the Pierre and Marie Curie, their daughter Irène and her husband, Frédéric Joliot, created radioactive elements by irradiating stable isotopes with alpha particles. At the time there was significant interest in the use of radioactive materials in medicine and this discovery allowed for the quick, economic creation of radioactive materials in larger quantities. Based on these discoveries, Irène and Frédéric Joliot-Curie won the Nobel Prize in Chemistry in 1935. The important research of the Joliot-Curies is in many ways the foundation of modern nuclear medicine and radiopharmaceutical research, as the production of radionuclides by bombarding stable isotopes with various types of particles is the key method of production of many of the most widely used radionuclides for nuclear medicine imaging and therapy.

George de Hevesy followed up on the work by the Joliot-Curies with his Nobel Prize–winning research on the use of radionuclides as tracers in the study of chemical processes, which paved the way for the development of radiopharmaceuticals that trace biochemical and physiological processes *in vivo* but do not produce any pharmacological effects.

The invention of the cyclotron in the early 1930s by Ernest Lawrence paved the way for the discovery of many biologically relevant artificially

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[1] For more information, see www.accessexcellence.org/AE/AEC/CC/historical_background.php [accessed July 5, 2012].

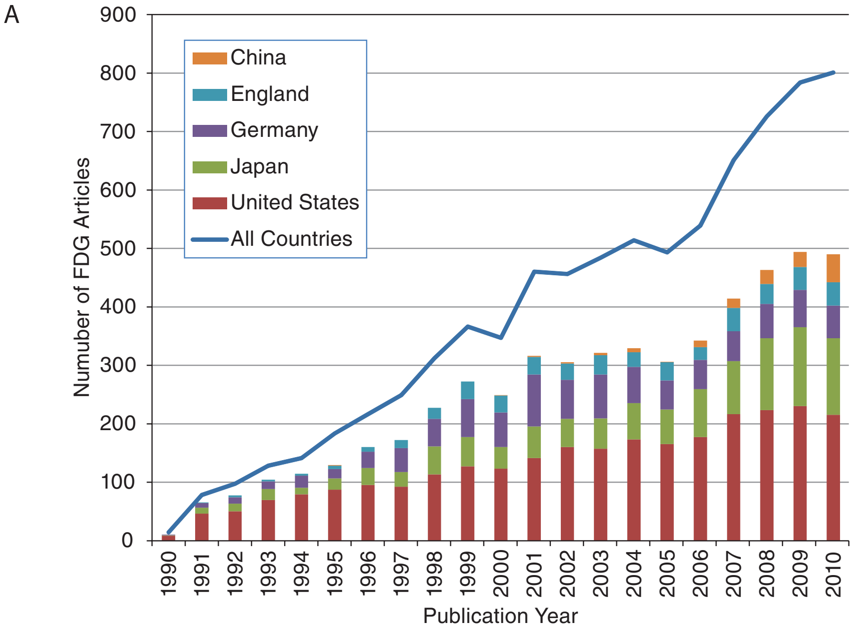
produced isotopes (e.g., iron-59, iodine-131, and technetium-99m) that have become invaluable nuclides for nuclear molecular imaging and therapy. John H. Lawrence, a physician, used his brother Ernest's radioisotopes in humans, treating a leukemia patient in 1937. John was also one of the early presidents of the Society of Nuclear Medicine (1966-1967). A colleague of the Lawrence brothers, Joseph G. Hamilton, coined the term "nuclear medicine" after observing John's treatments of people with radionuclides. In the late 1930s, Hamilton asked Nobel Laureate Glenn Seaborg if he could create a radioactive isotope of iodine with a half-life of about a week for studying thyroid metabolism, and Seaborg promptly produced radioiodine (iodine-133 or ^{131}I), which is still used for imaging and therapy of thyroid diseases.

After World War II there was enormous growth in the field of nuclear medicine. In 1946, a New York internist, Dr. Samuel M. Seidlin, together with colleagues Leo Marinelli and Eleanor Oshry at Montefiore Medical Center in New York City, treated and cured a patient with thyroid cancer using ^{131}I obtained from Oak Ridge National Laboratory. This work was published in the *Journal of the American Medical Association* (Seidlin et al. 1946) and produced a flurry of publicity. After this, there were almost yearly discoveries in the new field of nuclear medicine, in both chemistry and physics. The development of instruments to detect the various decays of radionuclides went hand in hand with new discoveries in radiopharmaceuticals.

No one could have predicted how valuable the cyclotron would become to modern molecular imaging for the production of a variety of radionuclides, especially the short-lived positron-emitting isotopes of carbon, nitrogen, oxygen, and fluorine. The availability of both small academic- and hospital-based cyclotrons spurred growth of the field and now regional cyclotron facilities have increased the availability of PET tracers, mostly through the production and distribution of 2-deoxy-2-[^{18}F]fluoro-D-glucose ([^{18}F]fluorodeoxyglucose, FDG), the most widely produced and indispensable molecular imaging agent. Figure 4-1A shows the international growth in publications about FDG since 1990. Figures 4-1B and 4-1C show the growth in publications for newer areas of nuclear medicine involving Fluorine-18 and Gallium-68. While the growth for both of these new areas is dominated by German- and U.S.-authored papers, more recently many other countries mostly in Europe and Asia are now contributing to the steep growth in numbers of publications in these areas.

RADIONUCLIDE PRODUCTION

There are three major sources for the production of radionuclides for nuclear medicine applications—particle accelerators (linear and cyclotrons),


A
Numuber of FDG Articles
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300
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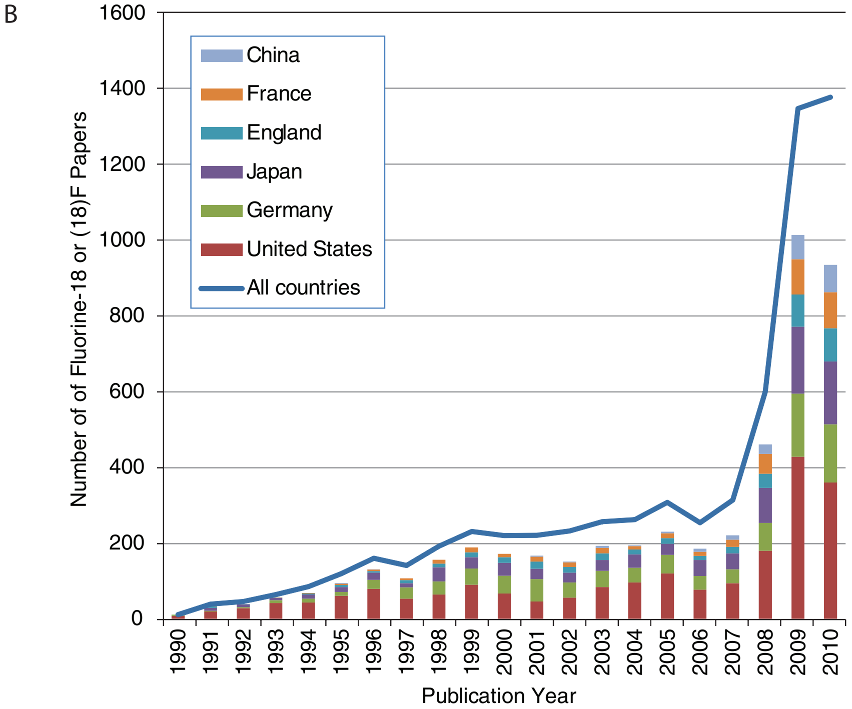
B
Number of of Fluorine-18 or (18)F Papers
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200
400
600
800
1000
1200
1400
1600
China
France
England
Japan
Germany
United States
All countries
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1991
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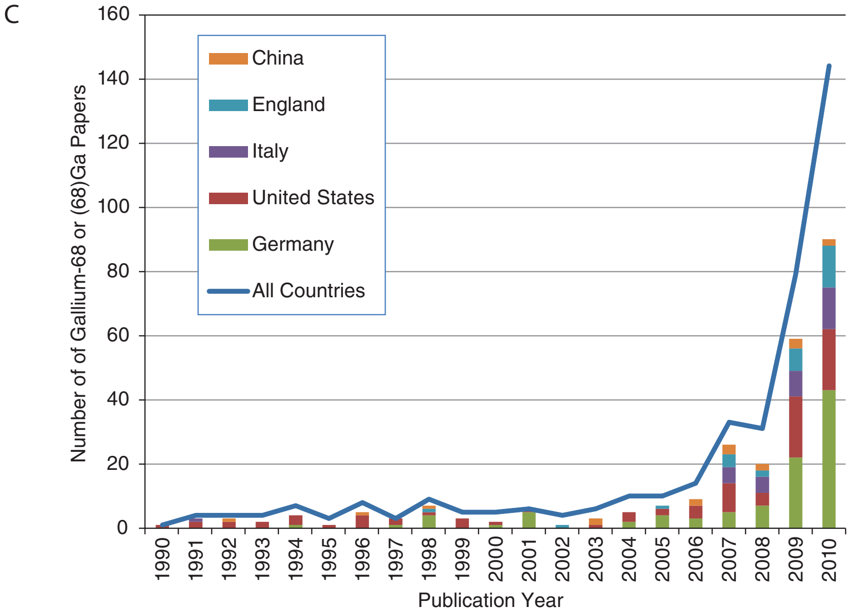


FIGURE 4-1 Keyword search of journal articles by country for nuclear medicine related keyword, 1978-2010. (A) fluorodeoxyglucose (FDG), (B) Fluorine-18 or (18)F, (C) Gallium-68 or (68)Gallium.
SOURCE: Web of Science keyword search, 2011.

nuclear reactors, and radioisotope generators. Most radioisotopes used for radiodiagnostics and radiotherapeutics are produced by cyclotrons. Figure 4-2 shows the distribution of cyclotron facilities across the United States. As of October 2011, there are over 150 cyclotrons in the United States that are operated by commercial entities, universities, or hospitals producing radiopharmaceuticals for PET centers (B. Clarke, SNM, personal communication, 2011). In addition to cyclotron-produced radioisotopes, nuclear reactors produce medical radioisotopes by either separation of isotopes from the fission materials (for example, $^{125/131}I$ and ^{99}Mo) or through neutron activation of stable isotopes (for example, ^{64}Cu from ^{64}Zn, or natural Zn targets). A listing of the common PET, SPECT, and radiotherapeutic isotopes used in nuclear medicine is provided in Table 4-1.

RADIOPHARMACEUTICAL CHEMISTRY

There are many aspects of the field of radiopharmaceutical chemistry, including radionuclide production, organic chemistry, inorganic chemistry,

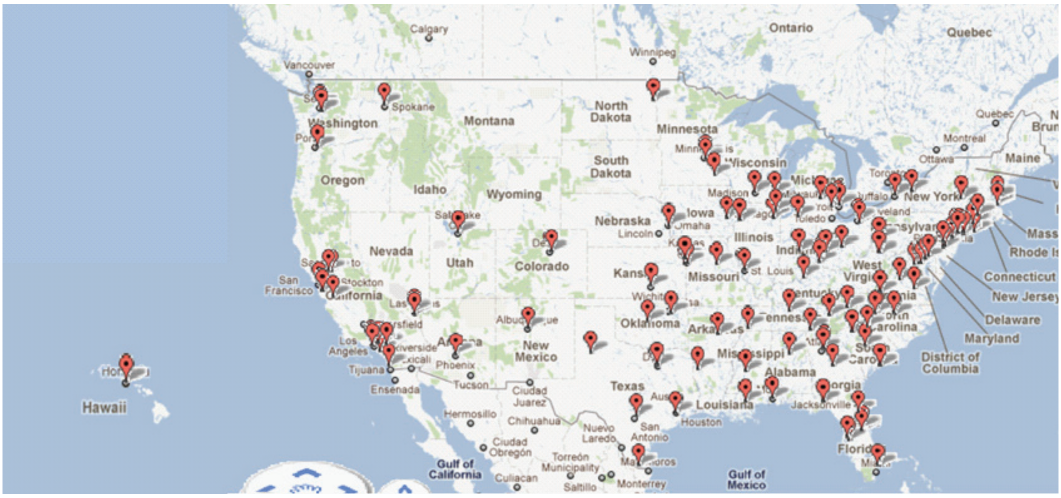


FIGURE 4-2 Map of U.S. commercial PET radiopharmacies using small, self-shielded cyclotrons that supply PET imaging probes for molecular imaging diagnostics used in patient care and research (does not include cyclotrons at medical schools).
SOURCE: B. Clarke, Society of Nuclear Medicine, personal communication, 2011.

biological chemistry, radiochemistry, automation (engineering), and regulatory science. The evaluation of novel radiopharmaceuticals in biological assays and animal models is vital to the successful translation of new agents into human studies. Prior to human studies, one must have knowledge of the production of radiopharmaceuticals for human use, which includes understanding federal regulations regarding production of the cold substrate, radionuclide, and radiopharmaceutical under good manufacturing practice guidelines. One must also have knowledge and proficiency in the safe handling of radioactivity—that is, radiation safety. Box 4-1 describes the various steps in the preparation of a radiopharmaceutical.

Radiopharmaceutical Research and Development

The development of radionuclide production requires extensive knowledge of nuclear reactions by bombardment of particles onto targets on a biomedical cyclotron or bombardment of neutrons on targets in a nuclear reactor. It is essential to apply nuclear and radiochemistry principles to maximize yields and to set the energies of the bombarding particles to optimize yields of the desired radionuclide and minimize production of longer-lived

TABLE 4-1 Widely Used Positron Emission Tomography, Single Photon Emission Computed Tomography, and Therapeutic Radionuclides for Imaging and Radiopharmaceutical Preparation

Isotope	Production Method Parent/Stable Isotope	Half-life
Positron Emission Tomography Radionuclides		
Fluorine-18	cyclotron (oxygen-18)	110 min
Carbon-11	cyclotron (nitrogen-14)	20 min
Nitrogen-13	cyclotron (oxygen-16)	10 min
Oxygen-15	cyclotron (nitrogen-14/15)	122 s
Copper-64	reactor (zinc-64) cyclotron (nickel-64)	12.7 h
Gallium-68	generator (germanium-68)	68 min
Rubidium-82	generator (strontium-82)	75 s
Zirconium-89	cyclotron (yttrium-89)	3.3 d
Iodine-124	cyclotron (tellurium-124)	4.2 d
Single Photon Emission Computed Tomography Radionuclides		
Gallium-67	cyclotron (zinc-68)	78 h
Technetium-99m	generator (molybdenum-99)	6 h
Indium-111	cyclotron (cadmium-111)	2.8 d
Iodine-123	cyclotron (xenon-124)	13.2 h
Iodine-131	reactor (tellurium-130)	8 d
Thallium-201	cyclotron (thallium-203)	3.1 d
Therapeutic Radionuclides		
Yttrium-90	reactor (strontium-90)	2.7 d
Iodine-131	reactor (tellurium-130)	8 d
Lutetium-177	reactor (ytterbium-176)	6.7 d
Rhenium-186	reactor (rhenium-185)	3.7 d
Strontium-89	reactor (strontium-88)	50.5 d
Samarium-153	reactor (samarium-152)	46.3 h

SOURCES: Cyclotron (2010); IAEA (2003, 2009); Unterweger et al. (2010).

byproduct radionuclides. A strong knowledge of targetry and separation chemistry is essential in order to produce high purity products.

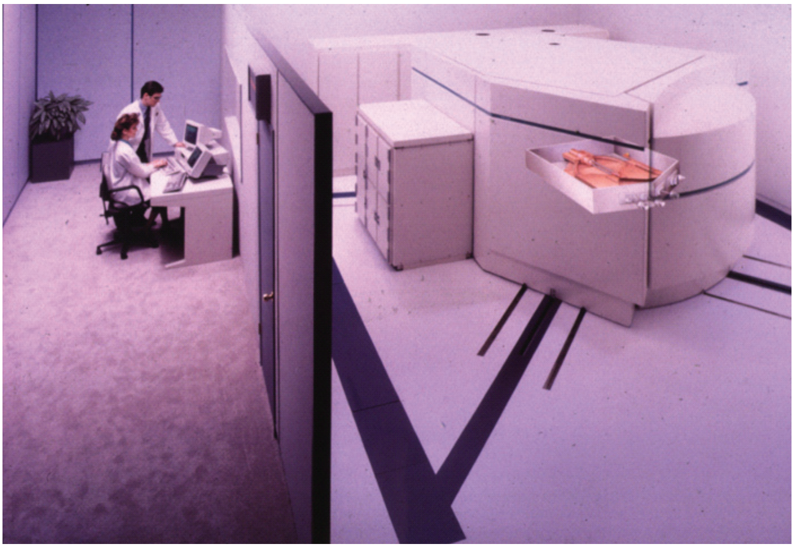
A solid working knowledge of organic chemistry combined with radiochemistry is required for the design of radiopharmaceuticals labeled with radiohalogens (for example, ^{18}F and radioiodines) and ^{11}C. In the past 40 or more years, there have been a large number of ^{18}F- and ^{11}C-labeled small molecules designed for imaging of cancer, cardiovascular disease, and neurological diseases. While there are a substantial and growing number of PET radiopharmaceuticals that are FDA approved under an Investigational New Drug (IND), only FDG has been approved by FDA for use in patient care under a New Drug Application (NDA). Examples of PET radiopharmaceuticals under FDA INDs include probes for imaging Alzheimer's plaques (Nelissen et al. 2009; Rowe et al. 2008; Wong et al. 2010), cellular prolif-

BOX 4-1 PREPARATION OF A RADIOPHARMACEUTICAL

There are a number of components that comprise the preparation of radiopharmaceuticals for clinical and research applications. Using fluorine-18 (^{18}F)-labeled fluorodeoxyglucose (FDG) as an example, the production process is highlighted below along with the radiochemistry emphasis areas that are associated with each part of the process.

Radionuclide Production

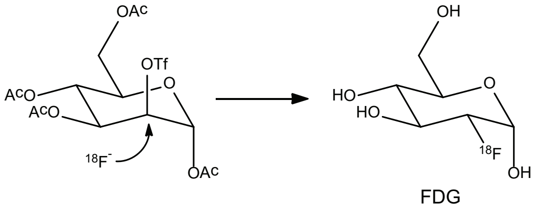
- Areas of expertise involved in this stage: cyclotron engineer and targetry chemist



Particles are accelerated by an accelerator (cyclotron, linear accelerator) or nuclear reactor react with the stable isotope nucleus to give an excited compound nucleus that emits a particle yielding the radioactive isotope.
Source: Image credits: The Crump Institute for Biological Imaging, Department of Pharmacology, University of California at Los Angeles. Brain & Mind. 2008. The cyclotron and PET [online]. Available: http://www.cerebromente.org.br/n01/pet/petcyclo.htm [accessed March 7, 2012].

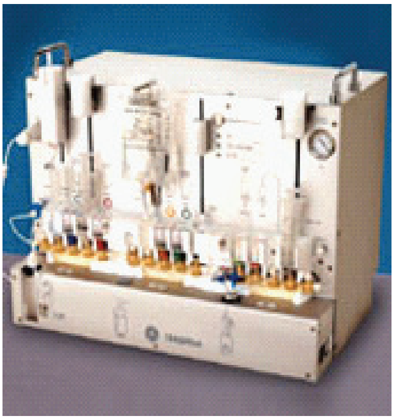
Radiopharmaceutical Chemistry

- Areas of expertise involved in this stage: radiochemist and nuclear pharmacist.



SOURCE: Henry VanBrocklin.

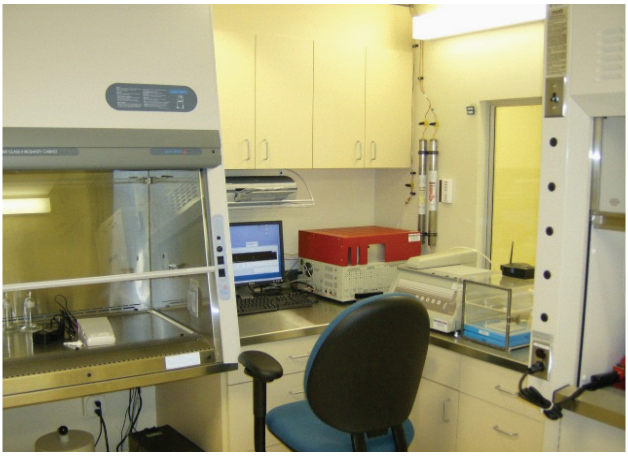
Fluorine-18 fluoride ion from the cyclotron is reacted with the 2-deoxymannosetriflate precursor. The ^{18}F-fluorodeoxyglucose tetraacetate intermediate is deprotected to give FDG. Automated chemistry synthesis units have been developed to provide reliable and reproducible batches of the radiopharmaceuticals and enhance chemist radiation protection.



SOURCE: Henry VanBrocklin.

Quality Control

- Areas of expertise involved in this stage: radiochemist and nuclear pharmacist.



SOURCE: Henry VanBrocklin.

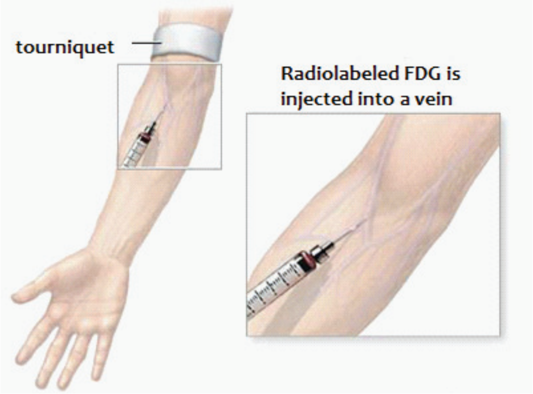
The quality of every dose preparation must be assessed prior to injection into the patient. A series of tests are conducted to assure that the product is sterile and free of contaminants that might be harmful to the patient.

(continued)

BOX 4-1 Continued

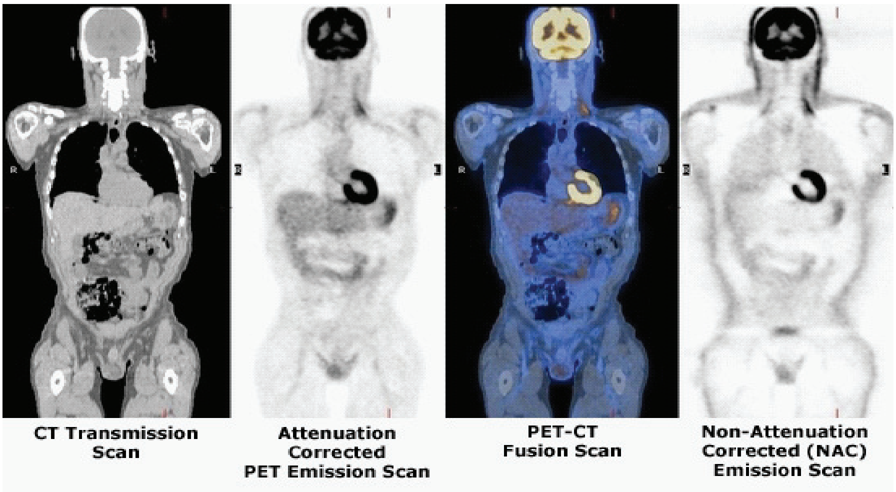
Patient Injection and PET Imaging

- Areas of expertise involved in this stage: nuclear medicine technologist, nuclear medicine physician, and medical physicist.



SOURCE: A.D.A.M., Inc.

Ten to twenty millicuries (mCi; 370-740 MBq) of FDG are injected intravenously 30 minutes prior to PET imaging



SOURCE: Henry VanBrocklin

PET and CT scans following the injection of FDG. Prominent FDG uptake is seen in the heart and brain because these are areas of high glucose metabolism. The fused PET/CT image combines the functional and anatomical scans in one image.

eration (Bading and Shields 2008) and hypoxia in cancer (Chitneni et al. 2011), and blood flow for cardiovascular disease (Maddahi et al. 2011) (see the Clinical Applications section later in this chapter).

Expertise in inorganic chemistry and radiochemistry has produced a burgeoning development of radiopharmaceuticals labeled with metal radionuclides, such as ^{68}Ga, ^{64}Cu, and ^{89}Zr. A critical component of developing these radiometal-labeled agents is the design of chelators that form stable complexes of the radiometals *in vivo*. This occurs as the release of radiometals causes a high uptake in radiation-sensitive tissues such as bone marrow, and results in poor target-tissue contrast due to high accumulation of the radiometals in blood and liver (Wadas et al. 2010). Many of the current clinical SPECT radiopharmaceuticals are ^{99m}Tc chelates. Altering the chelate backbone structure has led to a variety of imaging probes for bone, tumor, and heart and for brain blood flow.

Throughout the field of radiopharmaceutical chemistry is the theme of interweaving nuclear and radiochemistry with an understanding and practical knowledge of biochemistry, cell and molecular biology, and medicine. When modifying a known biological targeting molecule with either a radiohalogen (for example, ^{18}F or ^{123}I) or a radiometal (for example, ^{68}Ga, ^{64}Cu, ^{89}Zr, or ^{99m}Tc) chelate, one must first determine that the biological activity of the new compound is not significantly altered from that of the parent molecule. The biodistribution in normal rodents is performed to demonstrate that the agents do not accumulate in non-target tissues. This is followed by evaluation of the radiopharmaceutical uptake in target or diseased tissues. Validation that the radiopharmaceutical is specifically accumulating in its target tissue often requires use of microscopic techniques such as immunohistochemistry. Many iterations of optimizing the overall chemistry and specific radiochemistry followed by a biological evaluation is often required prior to choosing an agent for initial testing in humans. Moving agents into the clinic often requires collaborations of nuclear and radiochemists with cancer biologists, neuroscientists, and clinicians of various specialties. However, while it is important that nuclear and radiochemists embrace the many disciplines within the field of radiopharmaceutical sciences, the primary expertise of nuclear and radiochemistry is critical for success of this field.

Clinical Applications

For nuclear medicine imaging, a radiopharmaceutical is administered to the patient (typically intravenously) and a scanner that detects radioactivity in the patient is used to show the uptake of the tracer. Nuclear medicine images provide quantitative data on the biochemistry of normal tissues and disease conditions in living subjects in contrast to the anatomical imaging modalities (for example, computed tomography, ultrasound, and Magnetic Resonance Imaging), which primarily provide structural information. According to the Society of Nuclear Medicine's (SNM's) annual report for 2010, more than 20 million patients in the United States undergo nuclear medicine procedures for the diagnosis and treatment of a wide variety of diseases, including cancer, heart disease, and neurological diseases such as Alzheimer's disease (Center for Molecular Imaging, 2011).

A list of commercially available radiopharmaceuticals is provided in Appendix G. The majority of the tracers listed were approved prior to 1995. This is a direct result of the economics—that is, the cost of development vs. the potential market for the approved radiopharmaceutical—of bringing new entities through the full drug development and regulatory approval processes. While little has changed with FDA approval since 1995, there has been increasing pressure to develop new PET radiopharmaceuticals to augment the four currently approved PET radiopharmaceuticals (rubidium-82, ^{13}N-ammonia, sodium ^{18}F-fluoride, and ^{18}F-FDG). A small pipeline of PET and SPECT radiopharmaceuticals that are nearing approval has built up over the last 5 to 10 years. Several late-development stage radiopharmaceuticals and commercially available radiotherapeutics are also shown in Appendix G. The development and ultimate marketing of these new diagnostic and therapeutic radiopharmaceuticals is directly linked to the demand for trained radiopharmaceutical scientists at all skill levels.

NUCLEAR MEDICINE WORKFORCE

Nuclear and radiochemists in the area of nuclear medicine are mainly employed in academia and industry (Box 4-2). Within these two sectors, there are many sub-sectors. Academia entails scientists working in the basic science departments—that is, chemistry, biology, engineering—and scientists working in medical schools and in departments such as radiology or medicine. Hospitals affiliated with universities may have PET centers that provide FDG and other radiopharmaceuticals for clinical diagnostic imaging and clinical research. The industry sector is subdivided among companies that provide equipment and instrumentation for the nuclear medicine field (for example, cyclotrons, scanners, hot cells, and generators), companies that develop PET imaging probes, manufacture pharmaceuticals, and companies that develop and distribute radiopharmaceuticals. Many large pharmaceuticals developers such as Merck and Genentech, among others, now possess radiochemistry and nuclear imaging capabilities. This sector represents a growth area for radiochemistry where the existing and growing demand far exceeds the supply of radiochemists.

BOX 4-2 CAREERS IN NUCLEAR MEDICINE

Nuclear medicine is a highly multi-disciplinary field that involves many types of scientists and clinicians. Physicists and engineers develop and optimize charged particle accelerators and nuclear reactors for the production of radionuclides, as well as develop imaging instrumentation for the diagnosis of disease. Chemists design, synthesize, and radiolabel agents for diagnostic imaging and targeted radiotherapy of disease while biologists are involved in evaluating these agents using bioassays, cells grown in culture, and animal models of disease. Many scientists have a focus on one of these areas, but perform or lead research that involves multiple disciplines. Clinicians are typically board certified in radiology, nuclear medicine, radiation oncology, or internal medicine, although many have dual certifications. Regardless of the field of study in science, engineering, or medicine, the most critical and rate limiting disciplines in of nuclear medicine is nuclear and radiochemistry. Below is a sampling of the careers that are available to radiochemists who choose to enter the field of nuclear medicine.

Nuclear Pharmacist. According to the Board of Pharmacy Specialties, a nuclear pharmacist (also called a radiopharmacist) is "a member of a nuclear medicine team who specializes in the procurement, compounding, quality control testing, dispensing, distribution, and monitoring of radiopharmaceuticals" (BPS 2012). Nuclear pharmacists are employed by hospitals, academic medical centers, or centralized radiopharmacies. These individuals typically have either a doctorate in pharmacy or are registered pharmacists. After obtaining their degree, they pursue continuing education in the form of certification in nuclear pharmacy (for example, through the certification program at Purdue University) or radiopharmacy (for example, through the certification program at the University of New Mexico).

Industrial careers. Positions in the nuclear medicine industry for radiochemists include nuclear medicine imaging, both pre-clinical and clinical, which is a key component of drug development. Pharmaceutical companies employ radiochemists to synthesize and radiolabel drugs of interest to determine their pharmacokinetics and target tissue uptake. These companies also perform clinical trials that incorporate PET and SPECT imaging to monitor whether their drug is effective at an earlier stage rather than following disease progression or remission. There are also companies that produce radiopharmaceuticals at centralized pharmacies, as well as companies that develop novel radiopharmaceuticals for PET and SPECT imaging.

Academic careers. There are many career opportunities in academia for radiochemists in the nuclear medicine field at the B.S., M.S., and Ph.D. levels. The

(continued)

BOX 4-2 Continued

primary goals of Ph.D. radiochemists in academia are in the areas of research and education. Many of these positions are as tenure track faculty members and involve having a research group that includes undergraduate students, graduate students, postdoctoral trainees, and technicians. These faculty members may also teach courses in the area of imaging and nuclear medicine. Faculty members who are engaged in nuclear medicine research also either work at or direct cyclotron/PET facilities that produce radiopharmaceuticals for routine clinical studies and pre-clinical and clinical research. Aside from being a faculty member of a university, other career opportunities are as support staff that supervise or work in the PET/cyclotron facilities and also perform research in the labs of the faculty members. Nuclear pharmacists are also employed by academic universities and medical centers.

Government careers. The DOE national labs and the National Institutes of Health (NIH) employ nuclear and radiochemists involved in nuclear medicine research. NIH currently has at least six groups that are located in the National Institute of Biomedical Imaging and Bioengineering, the National Cancer Institute, the National Institute of Mental Health, the National Heart Lung and Blood Institute, and the NIH Clinical Center. These groups employ nuclear and radiochemists for developing radiopharmaceuticals for various diseases. These positions are typically either technical support or Ph.D.-level jobs that are research oriented. The focus of the national labs has shifted in the past several years away from biomedical research into the area of using radiotracers for energy-related research.

To determine the number of nuclear and radiochemists involved in nuclear medicine, the committee initially looked at a report on the nuclear medicine scientist workforce completed in 2006 by the SNM (Center for Health Workforce Studies, 2007). The report included survey data on physicians, nuclear pharmacists, physicists, and chemists. Out of the 898 survey respondents who indicated they were active in nuclear medicine science, 122 participants identified themselves as chemists. Those participants were asked to provide further information about their sub-specialization in chemistry, and, 36.9 percent selected radiochemistry as their major area of interest while an additional 21.3 percent indicated organic chemistry as their subspecialty.

To follow up on the 2006 survey and obtain more recent data, this committee received input (Table 4-2) from the radiochemist and nuclear pharmacist members of the SNM Radiopharmaceutical Sciences Council (RPSC) and

TABLE 4-2 Results of a Questionnaire Sent to Nuclear Medicine Radiochemists by the Society of Radiopharmaceutical Sciences/ Radiopharmaceutical Sciences Council of the Society of Nuclear Medicine

	No. of Yes Responses	% Yes Responses
U.S. Respondents (110)		
Use radiotracers as part of job	107	97%
Highest degree Ph.D.	78	72%
Primary discipline (nuclear, chemistry, radiochemistry, or radiopharmacy)	36	34%
Employed in		
academia	58	55%
industry	22	21%
medical facilities	9	9%
Hold faculty appointment	73	69%
in a radiology dept	39	58%
in a chemistry dept	4	5%

SOURCE: See Appendix D for questionnaire.

the members of the Society of Radiopharmaceutical Sciences (SRS).[2] There were a total of 110 responses received from U.S. members (110/425 or 25.9 percent response rate). The average age of the respondents was 52 (range: 26-83; median: 52). It was found that 34 percent of the respondents received their degrees in nuclear chemistry, radiochemistry, or radiopharmacy, which corresponds well with the 37 percent found in the earlier 2006 SNM survey (Center for Health Workforce Studies 2007).

Positions at the Bachelor's and Master's Degree Level

There are many positions requiring entry level B.S. and M.S. radiochemists in industry. For example, input to the committee from a sampling of industries that employ radiochemists in the nuclear medicine field (Table 4-3) show that 44 percent of the chemists employed have B.S. degrees, 30 percent have Ph.D.s, 20 percent have MS degrees, and 4 percent have A.A.S. degrees. Over the next 5 years, a 38 percent increase in the number of positions at the B.S./M.S. level at these companies is expected. This indicates the need for increasing training opportunities at the undergraduate level. Many, if not most, of the employees entering the nuclear medicine industrial workforce do not have any training in nuclear and radiochemistry

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[2] As of July 28, 2011, there were 760 unique members (425 from the United States) of the RPSC and SRS (Jennifer Mills, Society of Nuclear Medicine, personal Communication, July 28, 2011). See Appendix D for questionnaire.

TABLE 4-3 Estimated Number of Employees Currently Employed in Industry and a 5-year Projection of the Number of Employees Needed in Industry, Stratified by Highest Degree of Employee

	Current Number of Employees	5-year Projection of Required Employees
Associate's degree	7	27
Bachelor's degree	84	110
Master's degree	38	58
Doctorate degree	60	106
Total employees	189	301

SOURCE: Data kindly provided by the following companies: Abbott, ABT, Covidien, Eckert Ziegler, GE, Genentech, IBA, Immunomedics, Merck, NorthstarTM, Siemens, Sofie Biosciences, Pfizer, and UPPI.

and companies must rely on on-the-job training to educate their employees. A knowledgeable workforce will better serve this community.

Academic Sector Demand

Responses to the SRS/RPSC questionnaire also provided information on the ages of nuclear and radiochemists currently working in the academic sector of nuclear medicine. The average age of the academic survey respondents was 55 years, and 24 percent of the respondents were over the age of 60, suggesting that approximately 24 percent of the respondents will be of retirement age by 2016. This data suggests that a large component of the academic workforce will need to be replaced in the next 5-10 years. Much of the demand in academia is dependent on the federal funding climate. As of this writing, future federal funding from NIH and DOE for nuclear medicine based research is uncertain (see Figures 4-3 and 4-4 below for recent funding data). If federal funding dollars increase, the demand in academia will likely increase beyond that of replacing retired faculty and staff at universities.

Industrial Sector Demand

In order to determine the demand in the industrial sector, representatives from companies that are involved in the nuclear medicine industry that employ nuclear and radiochemists were contacted and asked for numbers of current employees and estimated demand over the coming 5 years. These companies were selected based upon their known activities in the area of nuclear and radiochemistry for the field of nuclear medicine. Table 4-5 summarizes the data obtained from 14 companies, with a response rate of

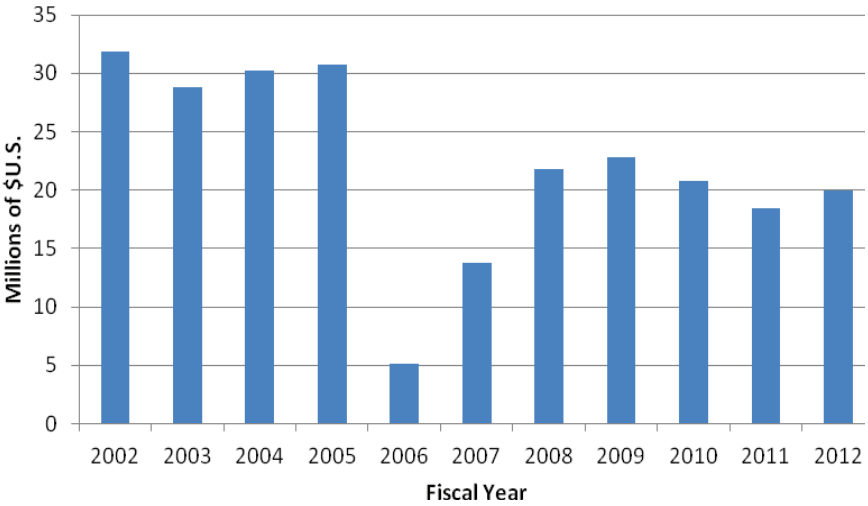

FIGURE 4-3 US Department of Energy funding for Radiochemistry and Imaging Instrumentation.
NOTE: Since 2010, the program name has been Radiochemistry and Imaging Instrumentation. Previously, other names were used: Radiopharmaceutical Design and Synthesis in FY 2005, Medical Applications in FY 2006 and FY 2007, Radiopharmaceuticals and Imaging in FY 2008, and Radiochemistry and Instrumentation in FY 2009.
SOURCE: DOE 2011.

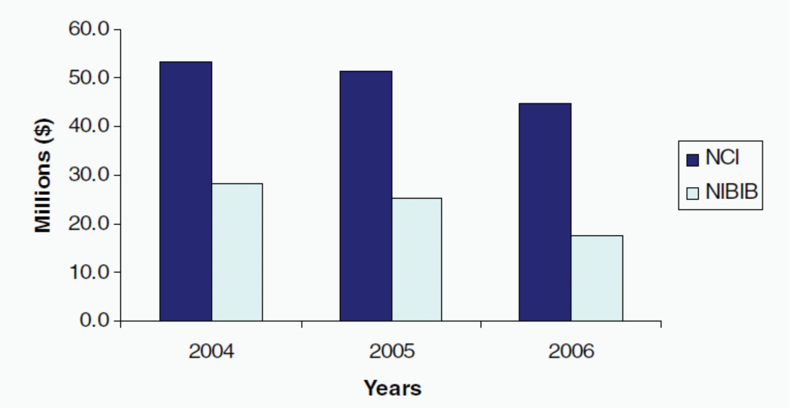

FIGURE 4-4 NIH Extramural funding for nuclear medicine research, 2004-2006. NCI, National Cancer Institute; NIBIB, National Institute of Biomedical Imaging and Bioengineering.
SOURCE: NRC/IOM 2007. Data originally provided by NCI and NIBIB.

88 percent. These data are not entirely representative, and there may be additional companies from which the committee neglected to obtain data. The data from the 14 companies suggest that there will likely be a large demand for trained nuclear and radiochemists in the next 5 years, with the projection being an approximately 60 percent increase in the nuclear medicine industrial workforce. In addition to nuclear and radiochemists being employed directly by the companies listed in the footnote of Table 4-3, many major companies outsource positions to academia, and an additional 40 full-time employees were reported from companies who responded to this question.

Government Sector Demand

U.S. national laboratories, NIH, and other agencies, including FDA and the National Institute of Standards and Technology, employ radiochemists and nuclear pharmacists involved in nuclear medicine research and regulatory activities. At the FDA, there are about a dozen employees who work in the Radioactive Drug Research Committee program in the Division of Medical Imaging Products.

There are at least six groups at NIH that employ radiochemists involved in nuclear medicine-related projects. A breakdown of the NIH radiochemists by degree is given in Table 4-4. The groups that employ radiochemists include the Laboratory of Molecular Imaging and Nanomedicine in the National Institute of Biomedical Imaging and Bioengineering, the Radioimmune Inorganic Chemistry Section of the Radiation Oncology branch at the National Cancer Institute, the NIH Clinical Center,the Imaging Probe Development Center at the National Heart Lung and Blood Institute, and two groups at the National Institute of Mental Health. Although there are projected budget cuts in the intramural program at NIH, most of these laboratories are projecting stable numbers of staff and trainees over the next 5 years.

TABLE 4-4 Estimated Number of Radiochemists Currently Employed at the National Institutes of Health, Stratified by Highest Degree

	Current Number of Employees
Pharmacy degree	4
Bachelor’s degree	5
Master’s degree	5
Doctorate degree	30
Total employees	44

SOURCE: Data were kindly provided by the following individuals: Martin Brechbiel (NCI); Gary Griffiths (NHLBI); Peter Herscovitch (NIH Clinical Center); Robert Innis (NIMH); Dale Kieswetter (NIBIB); and Victor Pike (NIMH).

ECONOMIC DRIVERS

The PET, SPECT, and Therapeutic Radiopharmaceutical Market in the United States

Recent market analyses indicate continued growth for nuclear medicine in both imaging and radiopharmaceutical development, which indicates the demand for nuclear and radiochemistry expertise will also continue. One report by Global Industry Analysts, Inc. (PR Web News Wire 2010), states that "nuclear medicine is one of the most promising and rapidly growing segments of the medical imaging industry." It says the global market for nuclear medicine is predicted to reach the US$1.69 billion by 2015, and attributes the growth to improvements in the development of molecular imaging-based diagnostics and treatments, along with an increased demand from the aging U.S. population. Another market report by Bio-tech Systems, Inc. (BTSI), states that the U.S. sales of SPECT and PET radiopharmaceuticals reached $1.16 billion in 2009, $1.20 billion in 2010, and are expected to rise to $6 billion by 2018 (BTSI 2006, 2010, 2011; PR Web News Wire 2009). BTSI's reports also detail how PET procedures grew 9 percent in 2009 to about 2 million, and grew to 2.1 million in 2010. In addition, sales of ^{18}F-labeled 2-FDG were increased from $276 million in 2009 to $299 million in 2010, consistent with the increased numbers of procedures.

As new agents are developed and approved by FDA and new products are introduced to consumers, total PET radiopharmaceutical sales are predicted to rise to $4.3 billion by 2018 (BTSI 2011), of which the majority of the increase will be from sales of new products other than FDG. For example, an FDA review panel unanimously recommended approval of a new PET agent (florbetapir) for imaging amyloid plaque associated with Alzheimer's disease, while two other similar agents (florbetabane and flumetamol) and an ^{18}F-labeled cardiac blood flow agent (flurpiridaz) are in phase 3 clinical trials. SPECT sales were down 9 percent in 2010, primarily due to reductions in pricing of perfusion agents, increased use of generic Sestamibi,[3] and the shortage of ^{99}Mo for ^{99m}Tc radiopharmaceuticals (BTSI 2011). The ^{99}Mo shortage was stabilized by the end of 2010 with two reactors back on line. The outlook for SPECT agents is improving, with a new agent, DaTscan (Ioflupane), recently approved for assisting in the evaluation of Parkinsonian syndromes.

In addition to the market for diagnostics, therapeutic radiopharmaceuticals include both current and emerging products for lymphoma, myeloma,

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[3] Sestamibi is a generic kit for the preparation of Technetium (Tc-99m).

and cancers of the breast, prostate, brain, liver, pancreas, and other types of cancer that are resistant to traditional therapies. The U.S. sales of therapeutic radiopharmaceuticals were $71 million in 2005, with rapid growth anticipated (BTSI 2006). There has been increased research activity in the area of therapeutic radiopharmaceuticals with a variety of molecular targeting strategies and therapeutic radionuclides for a wide range of tumor types. Although there are currently no approved alpha-emitting products, there is a strong push in research and development of agents labeled with ^{212}Bi, ^{213}Bi, ^{211}At, ^{223}Ra, and ^{210}Po. One agent, Alpharadin (^{223}Radium Chloride), recently closed successful phase III clinical trials and a 2012 filing for FDA approval is anticipated. This one agent alone may bring annual U.S. therapeutic radiopharmaceutical sales close to $1 billion by 2015 (PMLiVE 2012).

Research Funding

One of the underlying factors in creating the supply of expertise to meet the future demand is funding for basic research and education in nuclear medicine. Two of the key sources of funding over the years for basic and applied radiochemistry research with relevance to nuclear medicine have been the U.S. Department of Energy (DOE) Office of Science and Office of Biological and Environmental Research and NIH (Figures 4-3 and 4-4).

Drastic funding cuts, nearly eliminating the DOE Medical Applications program in FY2006, and the desire to focus research activities on DOE mission-driven programs, including biofuels production and climate change research and the DOE Office of Biological and Environmental Research, funding for the Radiochemistry and Imaging Instrumentation (RII; formerly called Medical Applications and Measurement Science Research subprogram) significantly altered the DOE nuclear medicine research landscape. The cuts included funding for "molecular nuclear medicine research, research and technology development activities in imaging gene expression, magnetoencephalography, biosensors, PET instrumentation for human clinical applications, MRI and neuroscience research, radiation dosimetry for therapeutic dose estimation, and targeted molecular radionuclide therapy" (DOE 2005, p. 258).

In 2008, Congress restored funding for the RII program, albeit at a reduced level from the FY 2005 allocation. The RII had funding opportunity announcements in FY2008 and FY2010 to support basic radiochemistry and imaging instrumentation research. In FY2009 the RII funded the DOE Integrated Radiochemistry Research Programs of Excellence, a training program that was recommended in the 2007 report *Advancing Nuclear Medicine Through Innovation* (NRC/IOM 2007).

These changes have been a significant programmatic shift for the RII program away from specific nuclear medicine applications to DOE mission centric applications of radiochemistry. While there are still opportunities for radiochemistry and imaging instrumentation, it is difficult for scientists in radiology departments and medical institutions to apply for these funds, given that they and their collaborators are not studying plant physiology and biofuel production. Overall, the reduction in congressional funding allocations to this program and the shift in research emphasis resulted in the loss of this valuable source of funding, which has had a negative impact on the nuclear medicine training pipeline for the future workforce and on valuable technology development resources that represented a significant return for the DOE investment.

NIH funding has supported many radiochemistry and imaging technology developments related to nuclear medicine (Figure 4-4).[4] The focus, however, has been largely on the applications of the radiotracers and translation into the clinic rather than on the underlying radiochemistry technology and new radiochemistry reactions. Since more recent NIH funding data for nuclear medicine were not available to the committee, it is not clear if NIH has been able to make up the difference created by the reduction in DOE funding, especially for nuclear medicine projects that are more basic science in nature. Funding increases from both DOE and NIH as well as other sources will likely be necessary to support the projected need for trained scientists and sustained future growth.

Health Care Regulations

Utilization of the technology in medical procedures also drives the supply and demand of the nuclear medicine workforce. The cost associated with a complete scan, including the radiotracer, professional fees, and scanner costs, all factor into the utilization of the technology. There is ongoing research in the area of cost effectiveness to determine the extent of health care savings offered by early diagnosis and staging, as well as the ability to determine patients' response to therapy prior to treatment or sooner after treatment. The magnitude of the importance of this is clear from the fact that across all diseases and all drugs, on average, only ~20% of patients treated have a measurable positive response, while ~80% take the risk with no benefit and enormous resources are lost to healthcare. Research demonstrating that the benefits of nuclear medicine outweigh the costs will have a

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[4] Note: The committee requested, but did not obtain more recent NIH nuclear medicine funding data.

positive impact on the demand for more nuclear and radiochemists in this field. Cost reimbursement by insurance and Centers for Medicare and Medicaid Services (CMS) will also dictate the utilization and growth of imaging technology, and thus employment of radiochemists. Flat or declining reimbursement will reduce growth. On the other hand, as the U.S. population ages, the number of imaging studies based on molecular diagnostics of the biology of disease is likely to increase. Since the leading molecular imaging technique is PET, the need for radiochemists will also increase.

The extent of the regulatory requirements, such as Medicare reimbursement and FDA oversight of radiopharmaceutical approval, on the industry may factor into the demand for radiochemists. Reimbursement for clinical nuclear medicine procedures dictated by CMS will determine the direction of growth or shrinkage in the field. Increased reimbursement equals growth in the number of procedures. Likewise, FDA regulations of radiopharmaceutical approval will determine the demand for radiochemists. Since 1995, while there are a substantial and growing number of radiopharmaceuticals that are FDA approved under an IND, there have only been seven radiopharmaceuticals or radiotherapeutics approved by the FDA with NDA for patient care (see Appendix G). Current regulations treat radiopharmaceuticals like therapeutics, not accounting for the major administered mass differences between tracer molecules and therapeutic drugs. Establishment of a new regulatory paradigm or regulatory discretion may lead to an increase of new tracers, supporting the need for more radiochemists

Finally, isotope availability is an important factor for the field. The lack of an adequate national supply of medical radioisotopes, especially ^{99}Mo, creates a reliance on foreign sources. Fluctuation in foreign supply streams creates an uncertain future for ^{99m}Tc radiopharmaceuticals. Development of a national facility for long-lived isotope production would reduce the foreign dependence and create more demand for radiochemists.

FINDING

The nuclear and radiochemistry workforce within the field of nuclear medicine is a vital and important component. Radiochemists and related disciplines support the infrastructure that is needed to prepare the imaging agents and radiotherapeutics for research and patient care. According to market reports and predictions from several company representatives, the field is growing and a significant increase in the number of trained personnel will be needed at every level of education (including B.S., M.S., Ph.D., and Phar.M.D.).

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5

Energy and Power Generation

INTRODUCTION

Energy, especially electrical energy, is a resource that is essential to the growth and maintenance of quality of life in contemporary civilization. According to the Energy Information Administration (EIA), "U.S. electricity use in 2010 was more than 13 times greater than electricity use in 1950" and is expected to grow in the long term (EIA 2011a). At present, coal is the dominant energy source for electricity production (Figure 5-1). A robust group of resources for energy production, transformation, and delivery is thus essential for national security. Although natural gas is a lower-carbon

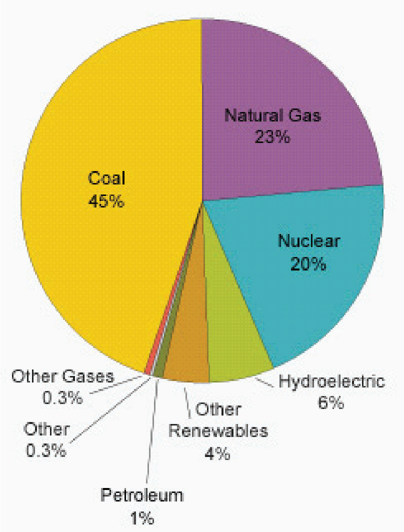

FIGURE 5-1 U.S. Net Electricity Generation by Fuel, 2010.
SOURCE: EIA 2011b, Figure 2, p. 1.

fossil fuel than coal, there is wide agreement that use of fossil fuels must be sharply reduced, at least for electricity production, in order to decrease their unfavorable impact on the environment, especially their release of carbon dioxide (CO_2) to the atmosphere. Nuclear energy has potential for significant expansion in order to alleviate CO_2 emission. Based upon long-standing U.S. national policy (Chu 2011): "Nuclear power will continue to be an important part of our energy mix, both in the United States and around the world. Its role grows more valuable as we confront a changing climate, increasing energy demand, and a struggling global economy." It is this committee's judgment that expertise in nuclear and radiochemistry is essential to ensuring that safe nuclear energy can remain part of the robust group of alternative energy sources for the United States.

The development of nuclear power is not a frontier fundamental research area of nuclear and radiochemistry, with the exception of chemical separations and some radiation chemistry topics, none of which appeared of general interest. However, the "back end" of the nuclear fuel cycle has many fundamental challenges. Box 5-1 represents the heart of the DOE Energy Frontier Research Center (EFRC) "Materials Science of Actinides," one of 46 EFRCs initiated in 2010 after intense competition, thorough peer review, and evaluation by DOE management. It describes beautiful molecular clusters that are truly novel and that may be relevant to colloidal transport of radionuclides in repositories. The work shows how radiochemistry overlaps with colloid chemistry and nanochemistry. Other basic-research radio/nuclear chemistry areas related to nuclear power (novel chemical separations for closed fuel cycles, nuclear fission cross-sections, etc.) are far less comprehensible to non-specialists.

A BRIEF HISTORY AND CURRENT STATUS OF NUCLEAR ENERGY

An exciting milestone toward utilizing nuclear energy occurred on December 20, 1951, when Argonne National Laboratory's reactor EBR-1 produced the first few kilowatts of nuclear electric power (Figure 5-3). In 1953, 8 years after the end of World War II, President Eisenhower spoke to the United Nations about peaceful uses of atomic energy. Five years later he opened the first atomic power station at Shippingport, Pennsylvania. In 1969, the first large-scale commercial nuclear power plant began operations in New Jersey.

The Oyster Creek Nuclear Generating Station in New Jersey was the first large-scale commercial nuclear power plant in the United States. It remains in commission as the oldest operating nuclear plant in the United States, having run since December 1969; its operator, Exelon Nuclear, plans to

BOX 5-1 ENERGY RESEARCH FRONTIERS CENTER: MATERIALS SCIENCE OF ACTINIDES

Fundamental aspects of chemical bonding of actinide elements, geochemistry of minerals, nanoscale materials, and migration of radionuclides under environmental conditions impact the nuclear fuel cycle. For example, there are very few minerals that contain peroxide because minerals form in the geosphere, where peroxide is unusual. However, the gamma radiation that exists in uranium-rich minerals produces peroxide and forms minerals with peroxide ions $(O\text{-}O)^{2-}$.

Similar gamma irradiation produces peroxide in groundwater near stored used nuclear fuel and near uranium-containing nuclear waste materials (Burns 2010). Within the past decade a large number of novel uranium clusters with peroxide and hydroxide have been found to self-assemble as nanospheres from aqueous solution (Figure 5-2).

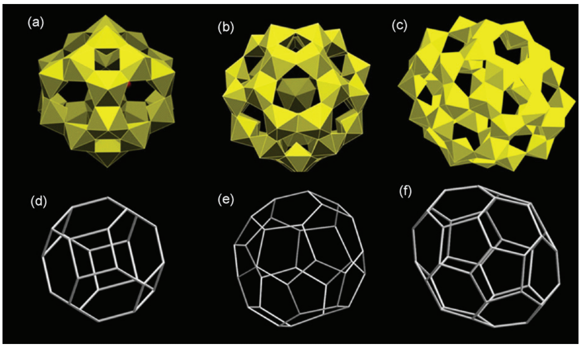

FIGURE 5-2 Clusters of uranyl peroxide hexagonal bipyramids containing topological squares. Shown are the polyhedral representations of the clusters (in yellow), and the topological graphs. (a,d) U24, (b,e) U32, (c,f) U40.
SOURCE: Burns 2010.

Most of these uranium clusters are spheroids with symmetry resembling, or even the same as, that of fullerene C_{60}. Other uranium clusters have been prepared as tubes or crowns, some forming very quickly and subsequently rearranging into more stable solids. Related clusters have been prepared with ions of the transuranium elements neptunium and plutonium. These colloidal-size clusters (monodispersed aggregates) may form at near-ambient temperatures in alkaline solutions that are part of the nuclear fuel cycle or under environmental conditions within a nuclear waste repository.

Colloids of similar sizes are sufficiently stable that they have been shown to transport radionuclides over significant distances, providing an unanticipated mode of radionuclide migration. These uranium-peroxide-hydroxide aggregates serve as an appropriate form to study, to understand, and to control the fundamental structure-property relationships of colloidal aggregates in solution. They represent a new class of nanoscale materials for fundamental study and for applied radiochemistry related to the nuclear fuel cycle.

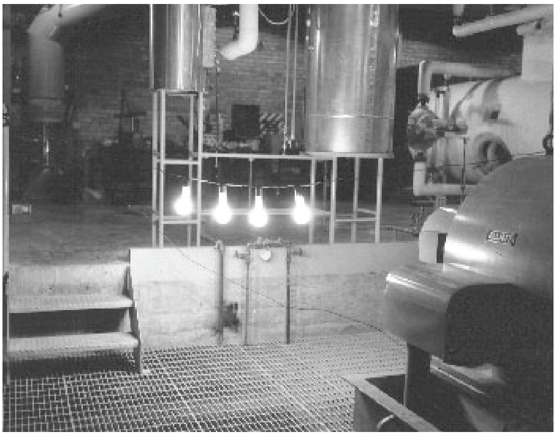

FIGURE 5-3 EBR-1 was the first nuclear reactor to generate electricity, providing power to light these four 200-watt light bulbs on December 20, 1951.
SOURCE: Argonne National Laboratory 2012.

close it in 2019. At present there are 104 nuclear power plants operating in the United States, producing 19.6 percent of all domestic electricity (NEI 2011a). As shown in Tables 5-1 and 5-2, the United States generates the most nuclear power in the world.

The first nuclear power plant in France was commissioned in 1971. With a sustained national commitment to nuclear power and nuclear deterrence, France has the largest worldwide percentage of its electricity from nuclear power (75 percent), produced by 58 reactors, the oldest having been commissioned in 1977 (World Nuclear Association 2011b).

The U.S. nuclear industry has had a sustained record of growth (Figures 5-4 and 5-5) and low production costs compared with other sources of electricity (Figure 5-6) for the past two decades, and a good safety record.[1] For example, the capacity factor (shown in Figure 5-4)—which is the ratio of the amount of power generated over a time period compared to the rated 100 percent power able to be generated in the same time period—at existing U.S. nuclear power plants it is expected to remain at approximately 91 percent for the next several years (USNRC 2011a, NEI 2012). Therefore, in 2010 the capacity factor of U.S. nuclear power plants was 91.2 percent; i.e., the U.S. plants produced 91.2 percent of the maximum power possible. The other 8.8 percent was when the plants were not at 100 percent power, for outages, to perform maintenance, or testing. Taken together, this information

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[1] For more information, see NEI 2011b

TABLE 5-1 Worldwide Nuclear Power Plants and Nuclear Electricity Generation*

	As of October 2011		Total for 2010	
Country	Number of Nuclear Units	Nuclear Capacity (MWe)	Nuclear Generation (BkWh)	Nuclear Fuel Share (Percent) of Electricity
Total	431	367476	2630.2	
United States	104	101229	807.1	19.6
France	58	63130	410.1	74.1
Japan	51	44642	280.3	29.2
Russia	32	23084	159.4	17.1
Korea RO (South)	21	18716	141.9	32.2
Germany	9	12003	133.0	28.4
Canada	17	12044	85.5	15.1
Ukraine	15	13168	84.0	48.1
China	14	11271	71.0	1.8
Spain	8	7448	59.3	20.1
United Kingdom	18	10962	56.9	15.7
Sweden	10	9399	55.7	38.1
Belgium	7	5943	45.7	51.2
Taiwan	6	4927	39.9	19.3
Czech Republic	6	3722	26.4	33.2
Switzerland	5	3252	25.3	38.0
Finland	4	2721	21.9	28.4
India	20	4385	20.5	2.9
Hungary	4	1880	14.7	42.1
Bulgaria	2	1906	14.2	33.1
Brazil	2	1901	13.9	3.1
Slovakia	4	1816	13.5	51.8
South Africa	2	1800	12.9	5.2
Romania	2	1310	10.7	19.5
Argentina	2	935	6.7	5.9
Mexico	2	1600	5.6	3.6
Slovenia	1	696	5.4	37.3
Netherlands	1	485	3.8	3.4
Pakistan	3	725	2.6	2.6
Armenia	1	376	2.3	39.4

* Sorted in order of 2010 nuclear generation. IAEA and WNA nuclear capacity figures vary slightly.
SOURCE: Reprinted with permission. IAEA 2011; World Nuclear Association 2011a.

indicates that nuclear energy will continue to be a part of the U.S. energy portfolio for the foreseeable future, and thus an employment sector requiring nuclear chemistry expertise.

In addition, there are several plants that are performing power upgrades, which add additional capacity to those units. On the new generation front, due to the historically low price for natural gas it is expected that new natural gas plants will be built and operated to replace the older coal plants and to cover increases in demand. Overall, the nuclear share of electricity generation in the United States is projected to remain stable or on a slight

TABLE 5-2 World Nuclear Fraction of Total Electricity Production for Selected Countries in 2010

Country	Share of world nuclear electricity generation (6 largest)	Nuclear fraction of country's total electricity production
United States	30.6%	19.6%
France	15.6%	74.1%
Japan	10.6%	29.2%
Russia	6.1%	17.1%
South Korea	5.4%	32.2%
Germany	5.1%	28.4%

SOURCE: EIA 2011c ; World Nuclear Association 2011a.

decreasing trend over the next decade (EIA 2011g; NEI 2011e). Although the United States has the longest history of production of nuclear energy and the largest nuclear generating capacity, France currently has the most ambitious nuclear program with the world's largest percentage of electricity production from nuclear reactors. Therefore, this report considers the French university and engineering academic nuclear chemistry institutions and French industrial training infrastructure as a useful model.

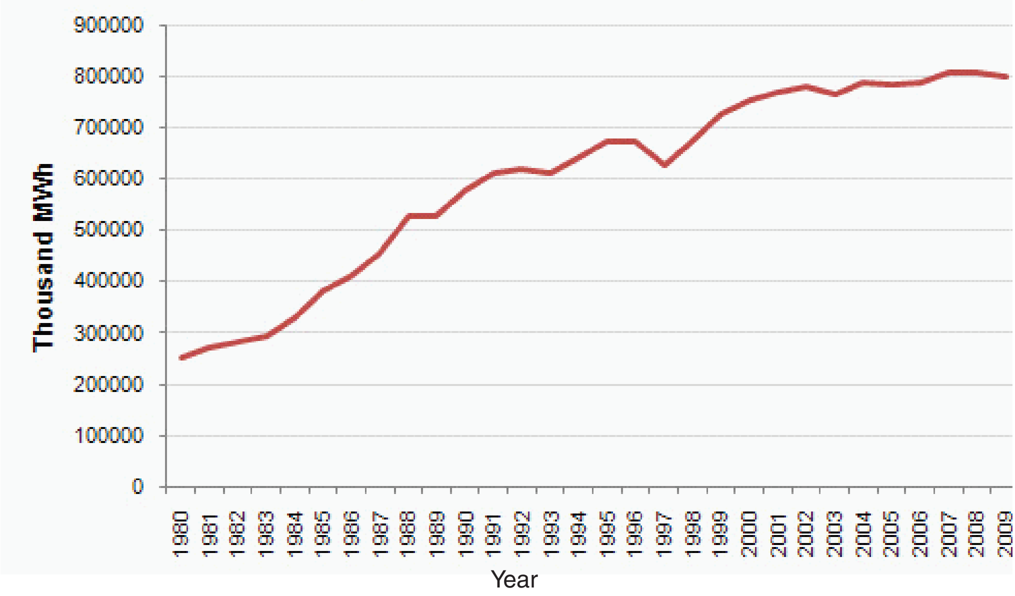

FIGURE 5-4 Growth of U.S. nuclear energy generation, 1980-2009.
SOURCE: EIA 2011d,e.

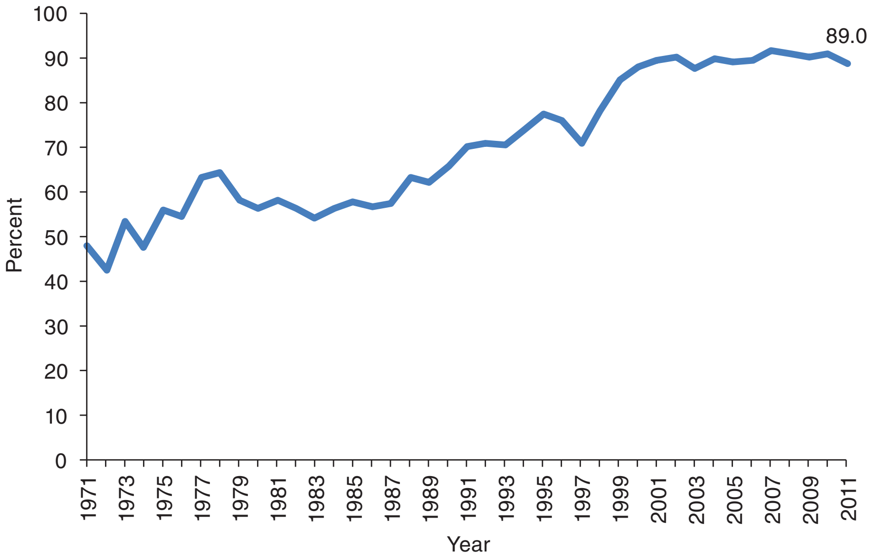

FIGURE 5-5 U.S. nuclear industry capacity factors—the ratio of the amount of power generated over a time period compared to the rated 100% power able to be generated in the same time period, 1971-2011. For comparison, France's capacity factor was 75 percent in 2011. (World Nuclear Association 2011b).
SOURCE: NEI 2011c.

WORKFORCE CONSIDERATIONS

Nuclear power produces nearly 20 percent of U.S. electrical energy. This level has been achieved through growth in the nuclear power industry between 1970 and 1990. Despite the absence of nuclear power plant launchings since 1977, this 20 percent level has been maintained since about 2000 by an increase in the industry's capacity factor to 90 percent. The reliability of delivery of nuclear energy (Figure 5-5) and its competitiveness with other sources of electric energy (Figure 5-6) underpin the nuclear power industry's ongoing need for well-trained mid-level professionals such as nuclear and radiochemists. The nuclear power industry requires professionals with nuclear and radiochemistry expertise in each of these domains:

- Design of advanced nuclear fission reactors and implementation of both transformational and incremental improvements in reactor technology;
- Operation of existing nuclear reactors;

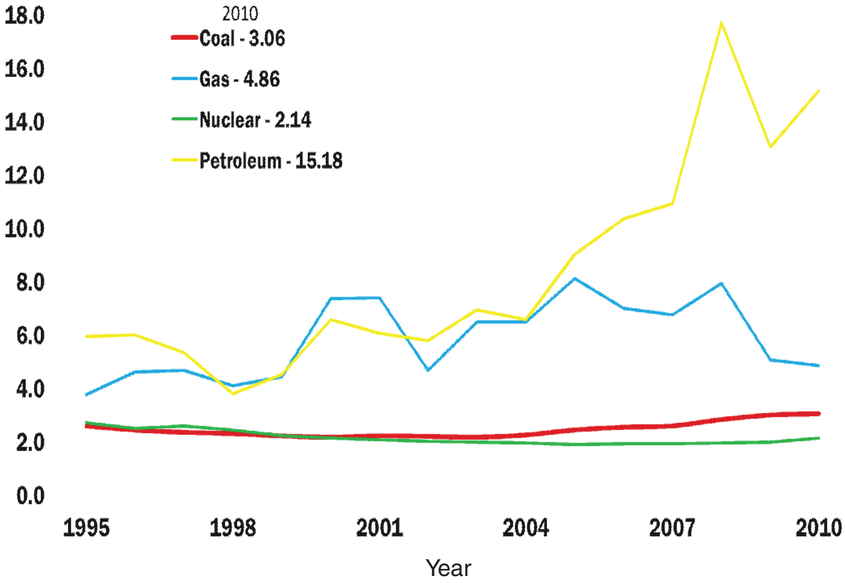

FIGURE 5-6 U.S. electricity production costs in 2010 cents per kilowatt-hour. Note that electricity production costs do not include the costs of construction, decommissioning, or indirect costs such as waste management or carbon capture.
SOURCE: NEI 2011c,d; data from EIA 2011f.

- Improvements and maintenance of components of the existing "open" nuclear fuel cycle;
- Storage and monitoring of used nuclear fuel;
- Safe and secure ultimate disposal of radioactive wastes streams from nuclear power plants;
- Environmental monitoring of all aspects of nuclear power; and
- Nuclear data (for example, half-lives, nuclear cross sections for neutronic processes including fission as a function of energy, and nuclear energy levels).

Bounding Scenarios

This chapter considers two bounding scenarios that will impact the future need for nuclear and radiochemistry expertise:

Scenario 1: Status quo

The first scenario (the lower bound) is that the existing civilian nuclear power reactor fleet is maintained, extending the operating life of the existing nuclear fleet to 60 years, where appropriate. This is slightly more conservative than the "reference case" of the U.S. Energy Information Administration's 2011 annual energy outlook (EIA 2011g, p.76), which assumes "3.8 gigawatts of expansion in the existing nuclear fleet with the completion of a second unit at the Watts Bar site, where construction on a partially completed plant has resumed."

Scenario 2: Ambitious

The second scenario (the upper bound) assumes an ambitious path forward: to build the U.S. nuclear fleet to the "greenhouse gas price economy-wide" case of the U.S. Energy Information Administration's 2011 annual energy outlook. In this scenario, "nuclear capacity additions from 2010 to 2035 will increase by 29 gigawatts as a consequence of the higher costs for operating fossil-fueled capacity." This is based on 20 new power plants being built within the next 20 years.

Specific Sector Demand

The U.S. commercial nuclear industry comprises workers at electric power companies, power plant design firms, and nuclear power industry suppliers. According to the Bureau of Labor Statistics (BLS), 2010 employment in the nuclear electric power generation industry (NAICS 221113) was 56,778 (BLS 2012). With the inclusion of power plant design firms and supplies, the Nuclear Energy Institute (NEI) estimates the nuclear industry employed 120,000 people in 2009, that 38 percent of that workforce will be eligible to retire within the next five year, and that the industry will need to hire about 25,000 workers by 2015 to maintain the current workforce (NEI 2010*)*. However, no further information is available on what fraction of that workforce consists of nuclear and radiochemistry experts, since the BLS has very little additional data on the nuclear industry. For example the BLS does not provide information on the occupations found in the nuclear industry nor is there information on the demographics of the nuclear industry workforce.

This committee contacted different groups of the nuclear power community to ask about the current and projected demand for nuclear and radiochemists over the next two decades. The responses received indicate a relatively small need for nuclear and radiochemists (when compared with the total nuclear industry workforce). However, the numbers are significant given the small size of the nuclear and radiochemistry workforce. The commercial nuclear power industry appears to be the segment with the most significant demand for radiochemists, particularly B.S. degree holders.

Overall, very few nuclear or radiochemists with advanced degrees will be needed at nuclear power plants.

Commercial Nuclear Power Plants

The standard organization at most nuclear power plants includes one radiochemist and one reactor chemist who is supported by chemistry technicians. Since there are 65 nuclear power plants in the United States, there are approximately 130 nuclear and radiochemists. Based on committee knowledge, out of the 130 approximately there are 4 M.S. and 1 Ph.D. level chemists, and the rest are bachelor's degree chemists. An informal e-mail questionnaire was sent to chemistry managers at the 65 U.S. nuclear power plant sites (a total of 28 companies, which are listed in Appendix I) resulted in only 27 manager responses (41 percent). Currently, almost all plants that responded hire B.S.-level chemists and train their own radiochemistry and reactor chemists. The following table (Table 5-3) quantifies the predicted hiring needs of nuclear and radiochemists for existing nuclear power plants (lower bound "status quo" scenario, extrapolated from 27 responses to all 65 requests).

Nuclear Power Vendor Community

The nuclear power vendor-support services community was also contacted by the committee. Out of five companies contacted four responded (Westinghouse, GE-Hitachi, AREVA, Dionex). Based on the input from the vendors, the committee estimates that there are currently about 5 B.S., 5 M.S., and 5 Ph.D. level nuclear and radiochemists total employed by the nuclear power vendor community. The predicted hiring of nuclear and radiochemists for the nuclear vendors and support industry were very modest. Extrapolating from 4 responses to all 5 vendors, there was a predicted

TABLE 5-3 Estimated Hiring Needs for Radiochemists at Existing Nuclear Power Plants (status quo scenario)

	0-5 y	6-10 y	11-15 y	16-20 y
B.S.	104	0	82	62
M.S.	6	0	0	0
Ph.D.	2	0	0	2

NOTE: Numbers based on extrapolation of 27 responses to 65 requests. Data is for retirement replacement only.
SOURCE: Unidentified respondents to questionnaire sent to companies listed in Appendix I.

need for 6 B.S., 3 M.S. and 3 Ph.D. level nuclear and radiochemists over the next 20 years.

Hiring needs for additional nuclear and radiochemists for the ambitious upper-bound scenario of 20 new power plants within 20 years are estimated to be all at the B.S. level: 20 B.S.-level radiochemists during years 6-10 and 20 during years 11-15. This would be in addition to the need given for the "status quo"scenario.

National Laboratories with Focus on Reactor and Fuel Cycle Research

Idaho National Laboratory (INL) has been designated since 2005 as the lead DOE laboratory for nuclear reactor research. Other national laboratories (especially Argonne and Oak Ridge) traditionally have had and still have missions of nuclear reactor research. Demographics and projected hiring for nuclear and radiochemists in the national laboratories are presented in Chapter 2 of this report. The projected demands at the B.S.-degree level for nuclear and radiochemists at national laboratories (see Table 2-4) are small compared to projected needs within commercial nuclear power plants. However, the projected demands for M.S. and Ph.D. nuclear and radiochemists at national laboratories are larger. Therefore the recommendations for nuclear and radiochemists in the energy and power sector focus on education needs at the bachelor's degree level.

Federal and State Nuclear Regulatory Agencies

Personnel data from the U.S. Nuclear Regulatory Commission (USNRC) indicate there may be a need for nuclear and radiochemists to replace retiring professional staff. As of December 2011, there were 3,995 total USNRC employees (USOPM 2012). Of these, 11 percent (432) had an occupation in the physical sciences (occupation code 13xx), mostly split between general physical sciences and health physics (occupational codes 1301 and 1306, respectively). However, there is no further data about educational degrees or area of expertise of the employees. Based on its own knowledge, the committee roughly estimates that 20 nuclear and radiochemistry professionals are currently employed at the USNRC at each degree level (14 percent of physical science employees). The committee further estimates that 3 M.S., and 4 Ph.D.-level nuclear and radiochemistry professionals will be needed by the U.S. NRC over the next 5 years to replace retiring staff. Projecting this estimate out over 20 years, the committee estimates that the USNRC will need 15 B.S.-, 12 M.S.-, and 16 Ph.D.-level replacement nuclear/

radiochemistry staff.[2] This assumption is conservative because it does not take into account any additional demand due to the construction of new nuclear plants *(see NRC Workforce projections* GAO 2007, USNRC 2011b).

Most states have an agency that regulates nuclear facilities, which often have staff with nuclear and radiochemistry expertise. For example, Maryland's Radiological Health Program fulfills this role for its one nuclear power reactor and other nuclear facilities. The Maryland agency was sent the same questionnaire that went to chemistry mangers at nuclear power plants, and responded that it employs one nuclear or radiochemist (Ph.D. level) and projects three hires within the next 15 years (1 B.S., 1 M.S., and 1 Ph.D.).[3] Based on the response from Maryland and there being 31 states with nuclear power plants, the committee roughly estimates that there are 10 B.S.-, 20 M.S.-, and 20 Ph.D.-level nuclear and radiochemists employed. In addition, a conservative extrapolation, estimating only 50 percent of the Maryland projection, it expected that state regulatory agencies will hire 15 B.S., 15 M.S., and 15 Ph.D. nuclear and radiochemists in the next 15 years.

Fusion Energy Workforce

For the purposes of this study, the committee did not consider fusion energy workforce needs. While it is not yet possible to suggest the size of a workforce that would be required by a fusion energy industry, research and development efforts within the fusion community do employ radiochemists, particularly in the development of diagnostics of fusion.

Overall Demand

Overall the demand in the nuclear energy and power area, including the USNRC, and state regulatory agencies, conservatively projects the need for nuclear and radiochemists as shown in Table 5-4.

These demands do not include national laboratory needs, some of which will be in the energy and power area. The current and projected demand for nuclear and radiochemistry expertise in the national laboratories are presented in Figure 2-5 and Table 2-4.

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[2] Estimate determined as follows: 3 M.S. and 4 Ph.D. needed for each 5-year period over 20 yrs, thus 3x4 M.S. degree holders plus 4x4 Ph.D. degree holders. There is also an estimated need of 15 B.S.-level nuclear and radiochemists.

[3] The questionnaire was also sent to representatives at state agencies in Illinois, New Jersey, and Pennsylvania, but no responses were received.

TABLE 5-4 Summary of Current and Projected Demand for Nuclear and Radiochemistry Expertise, Based on the Scenario 1—Status Quo Operation of Nuclear Power Plants

		To be hired . . .	
	Currently Employed*	. . .in the next 5 years	. . .in the next 20 years
B.S.	160	104	274
M.S.	49	14	36
Ph.D.	46	11	38

*Current employment: industry (125 B.S., 4 M.S., and 1 Ph.D.), vendors (5 B.S., 5 M.S., and 5 Ph.D.), USNRC (20 B.S., 20 M.S., and 20 Ph.D.), and state regulatory agencies (10 BS, 20 MS, and 20 Ph.D.). See text for more information.

FINDINGS

There is a critical need for nuclear and radiochemistry expertise in nuclear energy and power generation, especially at the B.S. level, based on a scenario of continued operation of nuclear power plants at current capacity:

- At the B.S. level, there is a high demand in the nuclear power industry for B.S. chemists, with a specialization in nuclear and radiochemistry. Largely due to estimates received from the U.S. nuclear power sector, there is a need over the next 20 years for approximately 274 B.S. chemistry graduates with an emphasis in nuclear or radiochemistry. Most training for nuclear or radiochemistry expertise among nuclear power operators is currently being done in-house by the industry.
- At the M.S. and Ph.D. levels, the demand in the nuclear power industry for nuclear and radiochemists with graduate degrees is small, but there is demand from federal and state regulatory agencies. The overall demand in the nuclear energy and power area (not including work at national laboratories) is projected to be 36 M.S. and 38 Ph.D. level nuclear and radiochemists over the next 20 years.

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6

National Security

INTRODUCTION

Following the discovery of fission in heavy elements ($Z \geq 90$) in 1938, developments in the field of nuclear science were driven by practical applications, and none more pressing than the potential for military application of fission energy release in "atom bombs." From the beginning, therefore, developments in nuclear and radiochemistry (and stewardship of these disciplines) have been closely associated with their application in national security; these missions continue to drive the need for fundamental research (see Box 3-1). From the initial development of nuclear weapons, expertise in fields of nuclear and radiochemistry have expanded to address a broader range of security-related challenges, including those in intelligence, nonproliferation, nuclear security and emergency response and, more recently, counterterrorism and homeland security. The growth in efforts beyond those associated with the nuclear stockpile is demonstrated in a recent interagency science and technology roadmap spearheaded by the Office of Science and Technology Policy (NSTC 2008). This effort outlines program areas contributing to "domestic nuclear defense." While many of these activities build on capabilities established to support the nuclear weapons program, future employment demands will naturally reflect application of these skills in a broader spectrum of programs.

Unlike some of the other application areas examined earlier in this report (for example, energy and medicine), workforce needs for nuclear and radiochemists in the area of national security are associated largely with mission-driven programmatic activities and with research, both funded by the federal government. In assessing the demand for the future workforce required to execute national security missions, it is necessary to examine needs arising from programs sponsored by a number of different government agencies.

Currently, the Departments of Energy (DOE) and Defense (DOD) share joint responsibility for nuclear weapons activities in the United States. The National Nuclear Security Administration (NNSA) within the DOE is charged with "ensuring a credible U.S. nuclear deterrent without nuclear testing and includes operations associated with surveillance, assessment, maintenance, refurbishment, manufacture, and dismantlement of nuclear weapons in the stockpile, as well as research and development and certification efforts. The NNSA nuclear weapons complex is comprised of DOE weapons labs, manufacturing plants, and facilities that carry out this mission" (DATSD[NM]), 2011). The NNSA also serves as the major agency funding work in nuclear nonproliferation and nuclear emergency response. Nearly all programs within NNSA are recognized to depend on nuclear science as a core discipline and nuclear and radiochemistry are considered critical skills needed to successfully execute its broad-based missions (Pruet and Rahn 2011). Other departments and agencies funding work that requires the expertise of nuclear and radiochemists include the DOD, Department of Homeland Security, Department of Justice, Department of State, and organizations within the intelligence community. Work supporting national security missions is carried out not only in the nuclear weapons complex, but in other national laboratories and in academic institutions.

TECHNICAL NEEDS AND WORKFORCE CONSIDERATIONS

Rather than presenting an inventory of staffing needs for each agency discussed above, the committee looked at the utilization of nuclear and radiochemistry expertise by major program area (weapons, nonproliferation and arms control, counterterrorism, and homeland security) and the likely resulting directions workforce demands will take based on the technical needs and possible bounding scenarios (or policy decisions).

Nuclear Weapons Program

Technical Needs

The earliest contributions of nuclear and radiochemists to the Manhattan Project in the 1940s were associated with the production and separation of fissionable material. As early as the Trinity test in 1945, nuclear and radiochemical methods were recognized for their potential use for diagnosing device performance. Within the nuclear weapons complex design laboratories (Lawrence Livermore National Laboratory [LLNL] and Los Alamos National Laboratory [LANL]), the traditional mission of nuclear and radiochemists was to support the Nuclear Test Program. This effort, often referred to simply as "radchem," included developing techniques and methods to determine the performance of nuclear devices by measuring radioisotopes produced first in aboveground tests and then, after the passage of the Limited Test Ban Treaty 1963, in underground tests. This effort required the development of ways to collect device debris and new methods for chemically separating reaction products from collected debris. Also required was the development of new and more precise ways of quantifying the radioactive isotopes whether they decayed by alpha or beta particle emission or the emission of gamma-rays and x-rays. Because of the varied decay paths of radioisotopes, their spectra are complicated and identification of radioisotopes required monitoring the change in the decay spectra as a function of time. Since both the energy and half-life were needed to verify and quantify radioactive reaction products, this drove the need for automation and the ability to handle and archive large amounts of data. Since not all reaction products are amenable to measurement by radiation detection (for example, some isotopes have long half lives or are nonradioactive), mass spectrometry techniques were also developed and utilized to enable the measurement of changes in isotopic ratios of elements and, as a result, nuclear reactions occurring during device detonation.[1] Thus, the "radchem" effort—in support of the Nuclear Test Program—led to advances in many areas, such as separations science, radiation detection, mass spectrometry, and instrument automation (including data acquisition systems and small-scale stand alone computers). These advances also involved pushing existing and emerging techniques to lower detection limits and higher energy resolution to maximize the information that could be derived from the analysis of device debris. These capabilities further enabled nuclear and radiochemists to devise and carry out experiments to obtain more accurate and a wider variety of fundamental nuclear data such as cross sections, decay schemes, and half-lives needed to interpret the post-test radiochemical data.

Following the cessation of nuclear testing in 1992, a science-based approach for annual certification of nuclear warheads with aging, replaced, or modified nuclear components was adopted by the DOE's Defense Program. The ability to certify performance of the U.S. nuclear stockpile in the absence of nuclear testing is embodied in what is now called the Stockpile Stewardship Program (SSP). The fundamental concept of the SSP is to:

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[1] Mass spectrometry also played an important role in fissile material production, especially with characterizing the feed, product, and tails streams from uranium enrichment and in analyzing irradiated uranium for plutonium production.

- Assess any discovered or introduced source of change in the nuclear components (aging, remanufacture, or design change) with high fidelity computer simulations,
- Use laboratory experiments and the nuclear test history to validate and improve particular aspects of the simulations (reducing uncertainties), and finally
- Apply improved and validated physics models in large-scale simulations to assess uncertainties and margins in the warheads.

However, as the stockpile continues to age, certification becomes an increasingly difficult task. Although many of the related issues are addressed by lifetime extension programs (LEPs), nuclear weapon systems continue to evolve beyond the conditions under which they were tested. To guide the certification approach and elucidate the specific details of physical phenomena that require experiments and improved models in simulation codes, a process called quantification of margins and uncertainties (QMU) was developed. The goal of the SSP is to have a predictive capability to extrapolate with confidence (high margins and low uncertainties) beyond the limited range of tested designs to ensure the performance, safety, and security of the U.S. stockpile.

Over the years, refinements to the SSP have been made and many of the data and models have been developed and implemented. However, the fundamental concept and the need for a science-based approach to certify the U.S. nuclear stockpile has remained the same. The technical approach developed for SSP has also proven useful for other security programs, especially where capabilities are needed to deal with emerging threats and technological surprises (DOE/NNSA 2011; Gordon 2002).

In the early years, the focus of nuclear and radiochemists supporting the Nuclear Test Program was to collect and analyze device postshot debris and to measure key nuclear data needed to interpret what was found in the debris. More recently, in the absence of testing, "radchem" efforts at the nuclear weapons design laboratories that support the SSP have evolved. The emphasis has shifted to the reinterpretation of data from old nuclear tests with the goal of meeting the needs of weapons designers who are working toward increased accuracy and a defensible uncertainty analysis. In addition, the development of new diagnostic tools and methods has focused on the ability to utilize data collected, but not used, during the Nuclear Test Program. Since 1992, "radchem" efforts have not significantly involved the utilization of nuclear and radiochemistry laboratory capabilities that were prominently used before the end of testing; however, in the last few years interest has emerged in developing new diagnostics based on radionuclides still present in archived debris samples.

In addition to measuring radioisotopes produced in nuclear tests, nuclear and radiochemists have a long-standing expertise in measuring and evaluating the fundamental nuclear information necessary to interpret the debris measurements. Most familiar to the SSP are the nuclear reaction cross-section sets necessary for determining performance of nuclear weapons; recently, the uncertainties associated with the fission-chain yields, which are necessary for the interpretation of fission product concentrations, as a number of fissions have received a lot of attention. The measurement of fission chain yields is a classical radiochemical problem and any current discrepancy among datasets can best be resolved with experimental measurements. Two important uncertainties in radiochemical device diagnostics are 1) the destruction and creation of radionuclides from a device, and 2) the degree to which physical properties (for example, volatility) change the distribution of radionuclides in post-shot debris. Reducing and quantifying these uncertainties requires, among other things, high quality nuclear data. In particular, precise cross-section data on neutron induced reactions such as (n,γ), (n,2n), and (n,f) on materials and the production and destruction of the prompt (precursor) fission products are needed to validate physics models and reduce uncertainties in predicted device performance. To address the uncertainties associated with chemical volatility mentioned above, a multi-disciplinary approach is required that includes, theory, experiment, and simulation. Nuclear and radiochemistry are the key players in developing this understanding.

Determining device performance is a very challenging and complex problem for the SSP. Since an underground nuclear test represents an integral test of a very complicated device, to infer performance from the interpretation of reaction products requires making some simplifying assumptions. Understanding the impact and sensitivities of these assumptions is at the core of QMU for nuclear weapons certification and is essential for assessing margins and uncertainties in device performance. For the SSP, radiochemical data are the benchmarks against which the physics models in the large-scale simulations are validated; in addition, the data interpretations by nuclear and radiochemists form the basis for certification of the U.S. nuclear stockpile in the absence of nuclear testing.

Chemists and radiochemists are also integral to the characterization of materials, providing analytical data necessary for comparative certification of the performance of components in the stockpile. An essential requirement for certifying devices currently in the stockpile is to do a comparison of the material's properties—such as composition, strength, and hardness—against the properties of material that was tested with a device. Much of this effort is focused on the nuclear material, but it is also necessary to understand the long-term behavior of non-nuclear materials, including possible changes in material properties resulting from long term exposure to radiation due to radioactive decay.

Workforce Considerations

To accomplish work related to SSP at the weapons design laboratories requires a technical staff with not only the knowledge and expertise to handle, purify, and quantify radioactive materials, but also with knowledge and expertise to analyze and interpret nuclear and radiochemical data and understand its meaning in the appropriate context (broad–based system analysis approach). Furthermore, there is a significant constraint for persons holding these positions at the weapons design laboratory—they must be U.S. citizens and be able to obtain appropriate security clearances.

During the Nuclear Test Program, adequate funding for nuclear and radiochemists was available to execute a demanding programmatic mission (providing diagnostic support for a steady stream of tests) and to maintain a robust discipline in terms of support for fundamental research activities. The support for fundamental research activities at the design laboratories ensured that there was an invigorated staff working at the forefront of nuclear science and that state-of-the art science was being brought to bear on the programmatic mission. Having a robust fundamental research program also allowed the design laboratories to compete for the “best and the brightest” students in the field and to recruit new staff that would become the next generation of nuclear stewards. After the end of the Nuclear Test Program in the early 1990s, the programmatic mission was scaled back considerably, and so too was the support of fundamental research for the discipline of nuclear and radiochemistry. As a result, staff with these skills migrated to other areas such as non-proliferation, environmental, and material science and the workforce supporting SSP declined substantially. NNSA reports that the size of its nuclear and radiochemistry workforce in the current program (approximately 20 individuals) is significantly smaller than it was prior to the end of testing in 1992 (Pruet and Rahn 2011). In this transition, a large number of highly skilled personnel also retired. Without a means of routinely exercising the skill base developed to support the SSP, many of these retirements occurred without passing a significant part of this specialized knowledge base along to the remaining workforce.

With an increase in programmatic and technical requirements associated with SSP, additional demands from other national security missions (see below) as well as the potential for new nuclear science programs such as those at the National Ignition Facility at LLNL, there is now an expectation that the size of this workforce may need to increase. Realizing this potential need, NNSA has commissioned the development of a technical "roadmap" from the weapons laboratories that is designed to assess and determine the stewardship needs and priorities for the nuclear and radiochemistry workforce over the next 20 years (Pruet and Rahn 2011). While the results of this effort and its associated program plan are not yet available, it is possible to present some bounding assumptions regarding future directions in the program and the demands these assumptions are likely to place on the future workforce.

Bounding Scenarios and Assumptions

Scenario 1: Status Quo

Nuclear weapons will continue to exist and the United States will maintain the ability to certify the performance of its nuclear stockpile as a strategic deterrent in the absence of nuclear testing. Under this scenario, reductions in size of the stockpile (and the need to extend the lifetime of existing systems) will continue to drive reinterpretation of historic radiochemical data for assessing margins and uncertainties to improve our scientific understanding of device performance. Aging and remanufacture of components will also require an improvement to the scientific underpinnings of stockpile stewardship.

- Certification of the stockpile without underground testing requires:
    - Improved physics models in simulation codes that are validated against high quality fundamental nuclear experimental data—such as neutron fission—and capture cross sections (probabilities), independent and cumulative fission yields (that is, "chain yields"), and decay properties.
    - Trained staff with the expertise to make the measurements described in the bullet above on a wide array of state-of-the-art experimental facilities, from particle accelerators and reactors to z-pinch and laser facilities—classical nuclear science experiments carried out with modern instrumentation in regimes made possible by state-of-the-art experimental facilities.

- ○ Staff with appropriate training, knowledge base, and experience working with and analyzing nuclear test data who are able to:
    - ▪ Provide credible and defensible uncertainty analyses of old test data as new and more accurate fundamental nuclear data becomes available—that is, can we answer old questions better today?
    - ▪ Mine existing device debris and archived data for additional information not possible at the time of the test—that is, do we know something different today?
    - ▪ Handle, purify, and quantify radioactive and stable materials (perform chemical and isotopic analysis) from archived device debris samples.
- ○ A better understanding of the chemistry of the actinide elements and key fission products, detectors, and tracers in underground nuclear tests.
- ○ Sustained capability to characterize nuclear materials through:
    - ▪ Analytical chemistry, or
    - ▪ Development of new analytical methods (for example, new methods that reduce waste volumes).
- ○ Knowledge of the effects of radiolysis on materials.

Given the challenges inherent in these missions, the required size of the laboratory workforce in nuclear and radiochemistry is likely to remain stable or increase somewhat, exploiting opportunities in both improving physical models and evaluating historical data. At a minimum, hiring is expected to keep up with attrition. However as time passes, the workforce to support the nuclear weapons mission will degrade if a means of routinely exercising the skill base developed to support the SSP is not supported, In any case, there is not likely to be a large change in the size of the workforce in either direction.

Scenario 2: Major Modification to the U.S. Nuclear Stockpile Is Required

This represents a growth scenario with a higher demand for nuclear and radiochemists compared to Scenario 1 (status quo). The modification may or may not imply an increase in the size of the stockpile. In either case, it is assumed that no testing of any modified weapon would be possible. This scenario also assumes there may be a need for additional production of fissile materials above that declared or additional chemical purification of existing material.[2]

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[2] If material production is required other supporting activities may be needed associated such as isotope enrichment, reactor production, material purification including hot cell separations,

- All of the requirements for status quo would be needed (theory, modeling, and large-scale simulations would be central; high quality experimental validation and fundamental nuclear data would be critical to success; and the ability to interpret radiochemical data to infer device performance would be paramount).
- If the size of the stockpile increases under this scenario, the speed required to get there will determine how much of an increase in the infrastructure and personnel will be required.
- There may be a requirement for separations chemists and facilities to chemically process nuclear material.

Under this scenario, an increase in the number of nuclear and radiochemists will be needed both to replace retiring staff and to supplement the current workforce. This scenario could include activities beyond continued development of the methodology for certification such as those needed to support production. The rate of adding new staff would depend in a complex way on the scope, schedule, and budget available to complete the work.

Scenario 3: Nuclear Weapon States Decide Multi-laterally to Eliminate Nuclear Weapons Entirely

Although this scenario could be regarded as one extreme associated with the future of the weapons program, this discussion of the ramifications more naturally falls within the area of nonproliferation and arms control and will be discussed further below.

Nonproliferation and Arms Control Programs

Technical Needs

Scientists involved with the Manhattan Project were among the first to recognize and express concern early in the development of nuclear weapons about the potential for proliferation of nuclear technology and nuclear materials. Likewise, when splitting the atom began to be exploited for commercial power production, similar concerns were raised.

The failure to control the spread of nuclear technology via post-war political efforts ultimately resulted in the need to develop technical approaches to safeguard materials and facilities. At the end of World War II, under the "Baruch Plan," the United States proposed to destroy existing

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and manufacturing capabilities. These activities would have a major impact and demand on the workforce across the entire Weapons Complex.

weapons if other countries would agree both to refrain from developing nuclear weapons and to permit inspections to verify their compliance with that agreement. Further, under this plan, the development of weapons and nuclear energy would have been under the purview and control of the United Nations Security Council. However, the Soviet Union objected and opted to conduct its own weapons development effort.

In 1953, President Eisenhower proposed to the United Nations General Assembly that an organization be established to promote the peaceful use of nuclear energy and to ensure that nuclear energy would not serve any military purposes. This resulted in the creation of the International Atomic Energy Agency (IAEA) in 1957. As countries including the United States, the Soviet Union, and France began to assist other countries with reactors and training, new discussions emerged regarding the need to control the spread of nuclear technology for military uses. Debate about "nonproliferation" in the United Nations General Assembly resulted in a resolution in 1961 stipulating that countries that already have nuclear weapons would not spread, or proliferate the associated technology and that countries without nuclear weapons would refrain from efforts to develop them. This resolution served as the basis for the Nuclear Nonproliferation Treaty (NPT) that was signed in 1968 and extended indefinitely in 1995.

Concurrent with the development of the NPT and a framework to address proliferation risks, a series of arms control treaties were negotiated, which created the need for science-based verification capabilities. Generally, these fall into the categories of limitations on nuclear testing (the Limited Test Ban Treaty of 1963, Threshold Test Ban Treaty of 1974, and the Comprehensive Test Ban Treaty of 1996) and arms limitation and reduction agreements (for example, 1972 Strategic Arms Limitation Treaty I, 1979 Strategic Arms Limitation Treaty II, 1991 Strategic Arms Reduction Treaty, and 1993 Strategic Arms Reduction Treaty II).

Both nonproliferation and arms control place technical requirements on the national security community that utilize the expertise of nuclear and radiochemists. The verification of treaties that limit nuclear testing often employs a variety of means to detect the detonation of explosive devices. If possible, it is very desirable to collect and examine debris to verify if an event detected was nuclear in origin. Such a determination is made through the identification of fission products and residual fissile material deemed to be the "signature" of a nuclear event. The techniques used to collect and analyze the debris are basically the same as the methods developed during the U.S atmospheric test program. The use of radiochemical methods to analyze debris collected from suspected nuclear events requires knowledge of fundamental nuclear data such as fission chain yields and radionuclide decay data and an understanding of the physical and chemical behavior of the components in the debris (for example, relative volatilities). This information is essential for addressing questions and explaining any observed inconsistencies in the radiochemical data from the collected debris. Although there can be differences in the detection of an event on foreign soil vs. a test in the United States (for example, the timescale of collecting samples and the types of specific information being sought), the same type of expertise is required for treaty verification as for the "radchem" work associated with the weapons program.

The technical approach for verifying compliance with nonproliferation and arms control agreements also draws upon a comparable base of nuclear and radiochemistry expertise. There are a number of objectives associated with safeguards and the inspection of known or suspected facilities. Some of these rely on simple measures of physical security, such as restricting site or facility access, or the use of seals, cameras, and other instruments to detect unreported movement of or tampering with materials. These physical inspections are complemented by extensive analyses and technical evaluations of the information gathered. Material accountability requirements invoke the need for systems to track all movement of nuclear materials into, out of, and within any nuclear facility. This can include accountability verification by sampling and analysis of nuclear materials where samples of nuclear (fissile) materials are taken at key measurement points of the process and subjected to destructive chemical and isotopic analysis. In other cases, the purpose of an inspection is to search for evidence of undeclared activity at a facility. In this case, samples from process streams (or swipe samples taken throughout a facility) can be analyzed by radiochemical methods to confirm or refute declarations regarding the explicit use of equipment or facilities (IAEA 2011).

Political developments in the area of nonproliferation and arms control impact the technical demands of these monitoring requirements. For example, "the Preparatory Commission for the Comprehensive Nuclear Test-Ban-Treaty Organization (CTBTO) was set up in 1996" and "tasked with building up the verification regime of the Comprehensive Nuclear Test-Ban-Treaty (CTBT) in preparation for the Treaty's entry into force" (CTBTO 2011). Among the elements of the verification regime is the International Monitoring System, a network of 321 radionuclide monitoring stations and 16 laboratories worldwide that were established to detect radioactive debris from atmospheric explosions or that escape from vented underground or underwater nuclear explosions. Analytical laboratories augment the monitoring stations to confirm findings and provide more precise radiochemical and isotopic data. Another element of the verification regime is the ability to conduct on-site inspections that are triggered by suspect or atypical events.

On-site inspections may include radionuclide sampling and analysis with a broader goal of distinguishing the source of the detected radionuclides (for example, a nuclear explosion from a natural source vs. reactors that are man-made) and a date the event occurred. The methodology employed in this case may differ from that associated with radionuclide monitoring stations and require additional expertise in areas such as sampling and the environmental behavior of radionuclides.

There is similar interest in expanding the methods employed in nuclear safeguards, stimulated by the adoption of the "Additional Protocol by the IAEA in 1997. Among other ramifications, the Additional Protocol gives IAEA the right to use environmental sampling during inspections at both declared and undeclared sites. It also allows for environmental sampling to be conducted over a wide area, not just at specific facilities" (ACA 2006). This introduces enhanced requirements for additional environmental sampling and radionuclide measurements associated with verification of the NPT, which in turn leads to in an increased need for nuclear and radiochemistry expertise. In addition to drawing upon technical knowledge of fission processes and radionuclide measurement systems, further expertise is required to understand radionuclide behavior and transport in the environment.

Workforce Considerations

A wide array of technical disciplines have been catalogued as contributing to the execution of programs in arms control and nonproliferation and to research efforts focused on improving methods in these fields (Lockwood et al. 2010). Nuclear and radiochemists contribute substantially to our ability to conduct destructive and non-destructive analyses on relevant samples.

Concerns have been raised in the United States and internationally regarding the future availability of an experienced workforce to contribute to these programs. In 2005, a Government Accountability Office report (GAO 2005) raised serious concern of a "looming human capital crisis," indicating that a significant percentage of international safeguards experts were close to retirement, and that there was an inadequate supply of workers being developed to address this gap. A recent study conducted by the Oak Ridge Institute for Scientific Education (ORISE) provided an assessment of the age distribution and estimated attrition over the next 15 years of the scientists and engineers working in the international safeguards area at nine DOE laboratories (chemists comprised 14 percent of this group). The study identified 250 international safeguards specialists who worked on Next Generation Safeguards Initiative-sponsored projects in FY 2009, and found that 41 percent of the workforce specializing in this area were 55 years of age or older and less than 20 percent of these same specialists were 44 years of age or younger (Lockwood et al. 2010.

The future demand for nuclear and radiochemists is likely to be impacted by the implementation of new arms control and nonproliferation treaties as well as by the verification requirements negotiated to supporting treaties. Several scenarios can be considered that bound the workforce requirements in this important area.

Bounding Scenarios and Assumptions

Scenario 1: Status Quo

In this scenario, current technical contributions to verification regimes are assumed to be maintained. Technical support is provided to the cooperative safeguards program and to international treaty monitoring efforts, but additional monitoring plans are not supported to any appreciable extent. The demographics of the current workforce make it difficult to train a new workforce for technical support in verification missions. This workforce is aging (as described above), heavily utilized, and lacks formal training in either higher education or vocational programs (i.e., the majority of current international safeguards specialists have not had any formal training).

- The need for a trained workforce is maintained at current levels with nuclear and radiochemists supporting the implementation of systems for environmental monitoring of radionuclides for treaty verification. There will be a higher rate of turnover of these workers, consistent with the need to replace skilled workers retiring, and more effort will be expended to provide on-the-job training for workers, where possible. Work will require:
    - Understanding fission processes and having a trained staff with the expertise to make a spectrum of radionuclide measurements in a variety of matrices.
    - Collaboration with geochemists on the maturation and validation of dispersion models to predict the fate of radionuclides in the environment (including underground and atmospheric) to localize source terms.
    - Development of advanced measurement systems to improve sensitivity of detection.
    - Nuclear and radiochemists who can continue to provide support for nuclear safeguards measurements and contribute significantly to advances in methodologies that make measurements

  more efficient, technologies that improve sensitivity, and the development of more field-deployable technologies. Similarly, there will be a higher replacement rate in the workforce to maintain stable staffing levels, since many current workers are nearing retirement.
  - Staff trained to measure actinide elements in safeguard samples, including low-level and trace measurements and isotopic analysis.

On the basis of the importance and priority given to safeguarding nuclear materials and facilities, it is likely that the number of trained nuclear and radiochemists that will be needed under this scenario will at least remain stable or grow slightly.

Scenario 2: Implementation of Additional Verification Regimes

Successful negotiation followed by ratification of additional treaties raises the possibility of additional verification technology requirements. This will include increased demands for onsite inspections that will drive new sampling and measurement requirements. Implementation of other verification methods associated with the IAEA Additional Protocol discussed earlier will necessitate an increase in the rate of processing radiochemical samples by supporting laboratories.

- Nuclear and radiochemists, in addition to providing the operational capability for destructive and non-destructive analysis of radionuclides (comparable to the technical requirements associated with scenario 1), are tasked with new demands for the development of increasingly sensitive and more precise and robust measurement systems for environmental measurements, particularly for the case of detecting and identifying undeclared facilities. This will require coupling knowledge of radionuclide behavior in the environment with novel systems for pre-concentration and separation or new methods for the simultaneous measurement of multiple component mixtures with or without minimal chemical separation process steps.
- Under conditions required for environmental monitoring, technical opportunities will exist to develop new sample collection methods. There will be significant challenges to address regarding the interpretation of analytical data from complex environmental matrices (including distinguishing signatures from environmental backgrounds).

- Opportunities may exist for novel approaches to safeguards measurements, extending capabilities beyond tracking the movement of materials to understanding actinide and radiochemistry (and associated nuclear materials processes); this understanding can suggest additional ways to monitor process facilities for attempted diversion.
- Opportunities also exist for knowledgeable personnel to look at facilities that are producing fissile material to make sure the material is not being diverted.

This scenario represents growth in both treaty monitoring and nuclear safeguards and is an issue for the United States and the international community. It is likely that, in addition to the issue of replacing staff at a rate commensurate with expected retirements, the number of trained nuclear and radiochemists that will be required to meet the new demands will likely increase. There will also be a need for nuclear and radiochemists with a broader range of technical capabilities to address new measurement needs.

Scenario 3: Nuclear Weapon States Decide Multi-laterally to Eliminate Nuclear Weapons Entirely

Any proposed drawdown in the number of nuclear weapons will entail discussions regarding the need for a responsive infrastructure. This will include knowledgeable personnel who are able to handle any technological surprises. It also includes the necessary infrastructure, including laboratories, equipment, and instrumentation.

- If nuclear weapons are abolished by the nuclear weapon states, it will take some time for dismantlement of the weapons and destruction of components and fissile material. Dismantlement and fissile material control, accountability, and final disposition will require a capable workforce and infrastructure.
- Global enforcement of “zero nuclear weapons” will require an organization (much like IAEA today) that is staffed with technical experts who are responsible for:
    - Inspections of declared facilities.
    - Inspections of potential new facilities.
    - Safeguarding materials for legitimate non-nuclear weapon purposes, such as:
        - Nuclear reactors for energy, research, and for the production of medical isotopes;

        - Any declared "excess" material that still exists from the nuclear weapons states; and
        - Potential military applications, such as reactor-powered naval vessels.
    - The United States would likely supply some of the workforce for such an organization as part of a "trust but verify" strategy.

Counterterrorism and Homeland Security

Technical Needs

The threat of nuclear and radiological terrorism has been recognized since the dawn of the nuclear age, but until the end of the cold war, was eclipsed by the threat of nuclear war with the Soviet Union. The need to address counterterrorism and homeland security generally emerged after the break-up of the Soviet Union when the incidence of nuclear smuggling began to rise; for example, the early to mid-1990s saw several widely publicized nuclear smuggling incidents occur in Europe. In December 1994, 2.7 kilograms of highly enriched uranium was seized in the back of a car in Prague, Czech Republic. This incident was widely reported in the press (e.g. Atkinson 1994, Gordon 1994) and drew attention to other seizures of weapons-useable nuclear material that had occurred in Germany, Russia, and Lithuania.

The seizures of illicitly trafficked nuclear materials in Prague and elsewhere created both public and government awareness of a growing problem. It was recognized by scientists that the technical analysis of nuclear and other radiological materials could produce information that would aid the investigation of nuclear smuggling incidents.[3] Nuclear forensic analysis of seized materials could, in principle, give clues about the origin of the materials (for example, how and when the materials were made and their intended purpose) that could assist in the identification of whose materials had been seized. Hence, the field of nuclear forensics was born.[4] In the

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[3] The term "radiological materials" is often used in the United States when describing or referring to radioactive materials. This term has appeared in many U.S. documents. The IAEA has promoted the use of the term "other radioactive materials" as the internationally accepted term for radiological materials.

[4] "Nuclear forensics is the collection, analysis and evaluation of radiological and nuclear material. It can be applied to material in a pre-detonation state, or to post-detonation radiological or nuclear materials, devices and debris; it also draws on information derived from the immediate effects created by a nuclear detonation. Nuclear forensics conclusions, fused with law enforcement and intelligence information, may support nuclear attribution—the identification of those responsible for planned and actual attacks" (Moody et al. 2005).

United States, the early efforts in the mid-1990s were funded mainly by DOE, with support from the Department of Justice. Nuclear forensics was viewed as primarily supporting law enforcement investigations.

In 1995, the International Technical Working Group on Nuclear Smuggling (often referred to as simply the ITWG) was created. The ITWG (since renamed the Nuclear Forensics International Technical Working Group) provides a forum where scientists, law enforcement personnel, and policy makers can discuss and explore issues surrounding the development, use, and implementation of nuclear forensic capabilities for responding to the illicit trafficking of nuclear materials and the threat of nuclear terrorism.

In 2004, the ITWG issued a document that describes the use of nuclear forensic analysis in response to incidents involving the seizure of illicit nuclear and radiological materials (Kristo et al. 2004). Subsequently, the IAEA used the ITWG report to form the basis of the report *Nuclear Forensics Support*, which was formally published by the IAEA (IAEA 2006). These documents describe the need for personnel trained in a number of technical fields, including the need for nuclear and radiochemists to support nuclear forensic investigations of seized nuclear and radiological materials.

In 2000, the Defense Science Board (DSB), which advises the Office of the Secretary of Defense within DOD, conducted a summer study that examined, among other issues, unconventional nuclear threats to the United States (DSB 2001). Such threats included the terrorist use of nuclear weapons (whether stolen or improvised) against the United States. The 2000 Defense Science Board study lead to a major research and development effort, funded by the Defense Threat Reduction Agency (DTRA 2011), to improve nuclear forensic capabilities, which are viewed as a vital component for developing a response to a nuclear event.

The events of September 11, 2001, elevated the issue of terrorist use of weapons of mass destruction (including nuclear weapons and radiological materials) to the forefront of U.S. government thought. Since 2001, the U.S. effort to develop and utilize nuclear forensics has evolved into the National Technical Nuclear Forensics (NTNF) capability. The basis for NTNF stems from both presidential directive and legislation and is an interagency effort that includes the Departments of Justice/Federal Bureau of Investigation,[5] DOD, DOE, Department of State, Office of the Director of National Intelligence, and the Department of Homeland Security. Furthermore, the Department of Homeland Security has created the National Technical Nuclear Forensics Center (NTNFC), which has, among other roles, the responsibility

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[5] The FBI is the lead federal agency responsible for the criminal investigation of terrorist events and the nuclear forensic investigation of a planned or actual attack.

to coordinate NTNF efforts among the U.S. government departments and agencies. The NTNFC was codified by legislation in 2010 (Nuclear Forensics and Attribution Act 2010).

The significance of the NTNF program is that it utilizes nuclear and radiochemistry as primary tools. The need for a well-trained workforce is fundamental to NTNF and the development, maintenance, and growth of such a workforce has been an important issue.

Workforce Considerations

The nuclear and radiochemistry aspects of counterterrorism and homeland security are essentially encompassed by nuclear forensic analysis, which represents the major "tool" with relevance to this programmatic area. In turn, the basis for performing nuclear forensic analysis drives a more fundamental need for nuclear data (for example, better cross sections and more accurate independent and cumulative fission yields) and the need for an array of reference materials that contain various nuclear and radiological materials. Within counterterrorism and homeland security, although areas that involve the detection of radioactive and nuclear materials (such as the Radiation Portal Monitoring Program and Second Line of Defense) depend more on nuclear and radiation detection and related disciplines, nuclear and radiochemists can also make contributions to needs in these areas.

Nuclear forensics analysis includes a wide array of technical disciplines that contribute both to the operational programs and to research and development into improving analytical methods, instrumentation, and data evaluation techniques (IAEA 2006). Nevertheless, nuclear and radiochemistry methods constitute a substantial part of the overall nuclear forensic analysis capability.

Concerns have been raised in the United States regarding the future availability of an experienced workforce to support nuclear forensics. Several recent reports [APS/AAAS 2008; GAO 2009; NRC 2010] have highlighted concerns about the extent of the workforce, the prospect that many in the field will be retiring in the next 10 years, and the growing awareness that there is an inadequate supply of workers being developed to address future needs. Workforce studies that focus on nuclear forensics (Wong 2011) mirror the results of studies done on other areas related to nuclear security (as described above).

As in other areas of nuclear security, the specific demand for nuclear and radiochemists within the future workforce for nuclear forensics will depend upon how the U.S. government continues to fund the various programs that directly support and impact the field. Counterterrorism and homeland security—which, for this report, primarily focus on nuclear forensics—provides a different situation than the other areas of nuclear security in that it is mainly threat-based. The NTNF program is being built to address high impact, low probability events. In the absence of actual events, the workload in NTNF consists of a combination of exercises, analysis of practice samples, instrument calibrations, and work derived from research and development to improve existing methods and develop new ones. The actual casework is limited, at best. Thus, nuclear forensics is driven by the need to be ready to respond to an event as opposed to having a routine workload. By comparison, the other nuclear security areas (for example, nuclear weapons and non-proliferation and arms control) deal with a more predictable workload (either for production and certification of weapons or for monitoring and verification of treaties and international agreements). For this reason, it is necessary to discuss workforce requirements in the context of building what amounts to an insurance policy.

Bounding Scenarios and Assumptions

Scenario 1: Status Quo

In this scenario, current technical capabilities that support counterterrorism and homeland security missions are maintained by leveraging existing assets, both human capital and infrastructure such as laboratories and radiochemical counting facilities, that were developed to support the nuclear weapons and nonproliferation and arms control program areas. This scenario represents a gradual decline in the required skill and knowledge base over time since new staff that will replace retiring staff will lack hands-on training and experience. Additionally, conflicts between the "day job" provided by the leveraged programs and the need for staff to remain current in nuclear forensic analysis will result in a less than robust and experienced workforce as the majority of staff that constitutes the nuclear forensic workforce will spend only a small fraction of their time actually doing nuclear forensics (Wong 2011).

The U.S. nuclear forensics capability will need a trained workforce that is maintained at current levels, with nuclear and radiochemists supporting the nuclear forensic analysis of samples. There will be a higher rate of turnover of these workers, consistent with the need to replace skilled workers retiring, and more effort will be expended, where possible, to provide on-the-job training for workers.

Nuclear forensic analysis involves the interpretation of a complex body of data and will require understanding and integrating:

- Production and utilization of nuclear materials,
- Production of radioactive isotopes by a variety of methods (reactor and accelerator-based irradiations),
- Fission processes and the associated production of fission products (both radioactive and non-radioactive),
- Techniques to measure a vast spectrum of radionuclides in a variety of matrices,
- Advanced measurement systems to improve the sensitivity of detection and the characterization of nuclear and radiological materials, and
- Pre- and post-detonation signatures.

It is likely that the number of trained nuclear and radiochemists employed under this scenario will at least remain stable, given the priority for maintaining a capability to respond to nuclear and radiological incidents.

Scenario 2: Development of a Stand-alone Program

In this scenario, the U.S. nuclear forensics capability would be funded at a level that reduces the need to leverage other programs. Under this scenario, an increase in the number of nuclear and radiochemists would be needed to both replace retiring staff and to supplement the current workforce. This workforce would also spend an increasingly larger fraction of their time supporting nuclear forensics, with a balance made between performing routine work (for example, analyzing samples) and conducting research and development activities supporting the nuclear forensics capability

FUTURE DIRECTIONS

Unlike many of the sectors discussed in this report, technical efforts in national security are by nature more restricted to the national laboratory workforce, due to the requirements for protection of classified information. There is no significant industrial sector outside of the national laboratories, and academic research relevant to national security programs are addressed in Chapter 2 and 3. The national laboratory workforce in this area performs work that spans the fields of weapons research, nonproliferation, and counterterrorism/homeland security. For this reason, the committee chose to address workforce demands for the entire workforce.

Workforce Demand and Attrition

In all the scenarios discussed above, there will be at least a sustained need to maintain the current workforce with nuclear and radiochemistry expertise. The national security stakeholders responsible for the major historic investment in this capability—the nuclear weapons program—can no longer support the magnitude and depth of the capability that was available in the testing era. However, the nuclear weapons program continues to drive the need for fundamental nuclear data. Over the years, other missions have benefitted significantly from past research and infrastructure investments provided by the nuclear weapons program. These other missions now represent a growing fraction of the market demand for nuclear and radiochemistry expertise in the national security arena. Most of the scenarios require an increased workforce. In addition to technologies for test and production monitoring as outlined above, a larger workforce may be needed to satisfy new requirements for verification of dismantlement of weapons and production and support facilities (APS 2010).

In the situations where the federal government supports most of the technical efforts carried out by nuclear and radiochemists, the number of staff is subject to annual budget cycles, making it difficult to project precise numbers for the size of the workforce. Another factor influencing the number of trained nuclear and radiochemists available to fill these government supported jobs is the attrition in the current workforce that is likely to occur over the next 10-20 years. Due to the classified aspects of much of the work in this area, the major employers are government laboratories (most associated with the DOE or DOD), although commercial laboratories have an important role, particularly in nuclear and radiochemistry for environmental sampling (for example, those associated with consequence management or public health programs). It is also worth noting that unique requirements exist for this workforce, such as the requirement of U.S. citizenship for those positions requiring security clearances. A large number of recent studies have highlighted concerns regarding the age demographics associated with the overall national security workforce (APS 2008, 2010; DSB 2008; Graham et al. 2008; Stimson 2009). Most cite, with concern, that nearly half of the workforce associated with the nuclear security enterprise (across all programs) is over 50.

The most quantitative treatment of the overall nuclear workforce was discussed in a report of the Defense Science Board Task Force on Nuclear Deterrence Skill (DSB 2008). This study noted aging in both the DOE and DOD civilian workforce, based on a survey of nearly 20,000 workers. The Task Force found that in 2007, 40 percent of DOE laboratory "essential workers" were over 50 and that more than 45 percent of DOE weapons plant workers were older than 50. The demographics associated with the DOD civilian workforce were comparable; 57 percent of DTRA "essential nuclear employees" were over 50, while 46 percent of the Navy's Strategic Systems Program essential employees were in this age range. Although this study did not explicitly look at programs in global security, this demographic has been echoed in reports that outline concerns associated with work in the fields of nonproliferation (Lockwood et al. 2010) and homeland security (NRC 2010).

In order to evaluate whether this demographic is applicable to nuclear chemistry and radiochemistry related fields, the committee obtained workforce data from the DOE national laboratories (See Chapter 2 and Appendix F), including those that have the most significant national security efforts requiring nuclear and radiochemistry. Available data suggests that the average age of the affected population (those in positions requiring nuclear or radiochemistry expertise) is close to 50 (average ages by lab range from 47 to 49). The percentage of employees with nuclear and radiochemistry skills who are 55 years of age or older range from 16-30 percent. In addition, previous reports have indicated that the workforce is not only aging, but in many cases expertise is limited to a single person (APS/AAAS 2008; and NRC 2010).

Corroborating data is found in more program-specific surveys. For example, the National Technical Nuclear Forensics Center within the Department of Homeland Security's Domestic Nuclear Detection Office has conducted a laboratory survey of the demographics of laboratory workers working in nuclear forensics and related programs. Of the individuals identified as being involved in nuclear forensics at eight national laboratories (not all of whom are designated as having expertise in nuclear and radiochemistry), 27.5 percent were 55 years of age or older (Wong 2011); the average age for various technical specialty areas ranged from 46 to 51.

These data suggest that the fields of nuclear and radiochemistry are demographically comparable to the general population in the nuclear security-related workforce and, as such, a significant number of retirements are expected over the next 5-10 years. Even if programs do not anticipate any growth in the need for these workers (and some scenarios do suggest no additional growth), a supply of expertise will be required to replace those lost to attrition.

Availability

The next question is whether the available supply of trained technical personnel will keep pace with the growing demand in the national security sector. Technical staff working in national security programs serve in a range of employment categories and require different degree levels. Staff scientists most commonly possess Ph.D.s; other staff categories require A.A.S., B.S., M.S., or other advanced degrees. The 2008 Defense Science Board study suggests that within the general area of nuclear deterrence skills, the armed services do not employ a preponderance of Ph.D.s (DSB, 2008); in contrast, DOE national laboratories have a larger percentage of Ph.D.-level employees. In the data collected from national laboratories for this study, most reporting laboratories cite 40-60 percent of positions requiring nuclear and radiochemistry expertise are at the Ph.D. level (see Figure 2-5). For purposes of this analysis, the focus was on the supply and demand of Ph.D.-level scientists, given that data is available on the production of relevant doctoral degrees. The workforce associated with other staff categories is likely to arise from the much broader cohort of chemistry or physics majors, with additional training being provided on the job; supply in these positions may not be the issue, but rather the adequacy of inclusion of nuclear and radiochemistry in undergraduate curriculum or the adequacy of the on-the-job training.

Unlike most of the employment sectors requiring nuclear and radiochemistry expertise, the special constraint of needing U.S. citizenship exists for national security programs. This significantly restricts the pool of available candidates; according to the National Science Board (NSB 2008; Finn 2010), non-U.S. citizens make up about 40 percent of the supply of scientists and engineers with doctorates. As discussed in Chapter 2 (see page 21), in chemistry as a whole, the percent of Ph.D. degrees awarded to U.S. citizens is about 50 percent,[6] while in nuclear chemistry about 70-80 percent of Ph.D. degrees have been awarded to U.S. citizens. A survey conducted in association with a study by the Nuclear Science Advisory Committee (NSAC) Subcommittee on Education indicated that, of graduate students in nuclear science surveyed at that time, 60 percent were U.S. citizens (NSAC 2004). However, the overall numbers of Ph.D. degrees in nuclear science are much smaller than science and engineering as a whole. Given this small pool of U.S. citizens, the fraction of the Ph.D.s available for national security work is quite fragile.

The concern over the pipeline of qualified personnel has not gone without notice. A number of the federal sponsors associated with national security work have recognized the issue and have instituted programs designed

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[6] National Science Foundation, WebCASPAR database [online] Year: All values; Citizenship (survey-specific): All values; Academic Discipline, Detailed (standardized): Chemistry; Number of Doctorate Recipients by Doctorate Institution (Sum); Citizenship (survey-specific).See https://webcaspar.nsf.gov/ (accessed November 1, 2011).

to develop their future workforce. In September 2007, DOE announced the Next Generation Safeguards Initiative, a program to revitalize the U.S. capacity to support IAEA safeguards. One of the elements of this effort is the Human Capital Development Program, the intent of which is to revitalize and expand the international safeguards human capital base by attracting and training a new generation of U.S. talent (Lockwood et al. 2010). Also, as previously mentioned, the Department of Homeland Security's Domestic Nuclear Detection Office (DNDO) instituted the National Nuclear Forensics Expertise Development Program, which was codified by legislation in 2010 (Nuclear Forensics and Attribution Act [2010]). This program received interagency support and includes secondary and undergraduate outreach, undergraduate and graduate student internships, graduate and post-graduate fellowships, university awards, and enhanced multi-year research and development funding and is discussed in more detail in Chapter 9 (Kentis and Ulicny 2009). These efforts are relatively young, so it is not yet possible to judge their efficacy in addressing the issue of workforce supply.

FINDINGS

Nuclear chemistry remains an essential capability for National Security. Nuclear and radiochemistry are disciplines that are increasing in importance within national security-related mission areas, judging from the spectrum of agencies funding this study and the interest expressed in presentations (Pruet and Rahn 2011; Wong 2011) on planning for the health of the disciplines. Developments in these science areas have been historically driven substantially by the nuclear weapons program. Although the scale and nature of its needs have evolved (from development of diagnostics for nuclear tests to a broader range of science improving our understanding of nuclear, physical, and chemical processes in weapons performance), nuclear and radiochemistry remains an essential capability for the weapons program, albeit one that currently supports a smaller core of practitioners than in the past. Some programs in national security, such as treaty monitoring, have utilized this weapons expertise for decades. Others, such as homeland security, are just emerging as efforts requiring these science areas. The committee judges that these two trends—reduced level of stewardship from the weapons program combined with increasing demand by other programs—now result in a situation where the capacity to "leverage" weapons staff will diminish over time. This will result in additional projected staffing needs in most scenarios.

The supply of nuclear and radiochemistry expertise for nuclear security requires training beyond what academia can provide. This has not been broadly recognized. There is a significant element of specialized development in certain programs that is required for new workers in the field. This comes in the form of on-the-job training, in which new workers (already academically trained) learn specialized applications of nuclear and radiochemistry. Given the lack of opportunity to learn these skills directly (for example, radiochemists cannot work on an active nuclear test program), this knowledge has to be transferred from senior workers. Funded work, however, rarely includes sufficient funding for knowledge transfer activities and the problem is increasing as budgets become more constrained. Unless these knowledge transfer activities are explicitly recognized, encouraged, and given resources, they will not occur; there is a significant risk of loss of critical capabilities.

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7

Environmental Management

INTRODUCTION

The environmental management (EM) component of the nuclear and radiochemistry workforce is that sector of the discipline dedicated to remediation and monitoring of the environmental legacy brought about primarily from many decades of nuclear weapons development and nuclear energy research. Specifically, EM nuclear and radiochemists are involved in all aspects of radioactive waste management, which includes civilian waste from the nuclear power industry and medical industry and non-civilian waste from the nuclear weapons programs and depleted uranium military programs. The role of the EM nuclear and radiochemist also includes routine regulatory monitoring of fabrication, processing, and disposal sites and fate and transport studies of U.S. Department of Energy (DOE) legacy sites—former World War II and cold war weapons production facilities—which include radioactive and chemical waste, environmental contamination, and hazardous material at over 100 sites across the country.

As shown in Figure 7.1, the DOE oversees cleanup of 23 DOE Office of Environmental Management (DOE-EM) sites in 14 states and 87 DOE Office of Legacy Management (DOE-LM) sites in 29 states (NCSL 2011).[1] For example, the DOE Hanford Site in southeastern Washington State contains 53 million gallons of chemical and radioactive waste resulting from more than 3 decades of plutonium production, which the DOE Office of River Protection is retrieving and treating to protect the nearby Columbia River (DOE 2010). If the United States pursues reprocessing of spent nuclear fuel as part of its long-term energy policy, then EM-trained nuclear and radiochemists would be involved in all fuel-cycle aspects of the nuclear power industry. This same workforce would also be among those asked to respond

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[1] DOE-EM is responsible for completing cleanup of legacy sites, while DOE-LM must manage remaining legacy responsibilities and commitments to former contractor workforce.

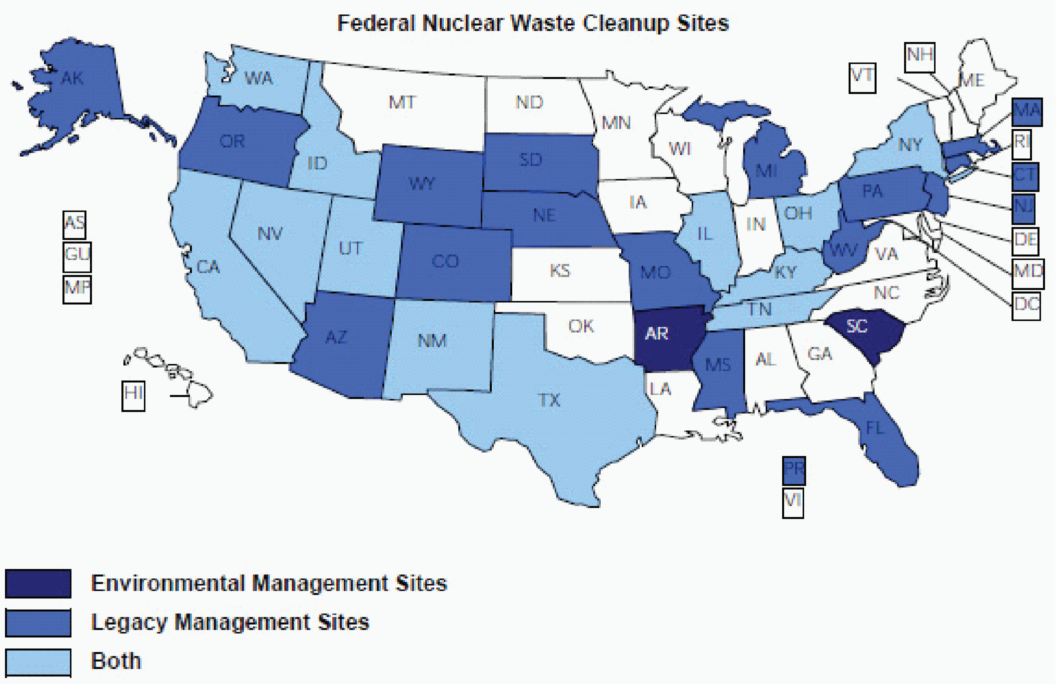

FIGURE 7-1 Nuclear Waste Cleanup Sites managed by U.S. Department of Energy Office of Environmental Management (DOE-EM) and Office of Legacy Management (DOE-LM).
SOURCE: NCSL 2011.

to site characterization and recovery in the event of a nuclear incident (both in the United States and abroad).

In many ways, the EM nuclear and radiochemistry field is broader than the other areas addressed by this committee, since it includes a very large range of radioisotopes and the chemical interactions of these isotopes in the environment. There is also a synergy between this field and others such as nuclear power, security, and medicine, since EM involves the disposal and monitoring of radiological material after its use in all other fields. There is also a natural connection between the nuclear and radiochemistry-trained personnel involved in nuclear forensics and those involved in EM. It is important to note that even if the United States decided to go completely nuclear free in the future, the EM workforce needs in terms of radiological monitoring and assessment would remain indefinitely. For example, the 2011-2020 strategic plan of the U.S Department of Energy Office of Legacy Management (DOE 2011, p. 5) states:

> Given the long-lived nature of radionuclides, long-term surveillance, monitoring, and maintenance at some [legacy] sites will be required for hundreds or even thousands of years. As time goes on, we will take any corrective actions necessary to modify engineered cells, treat contaminated groundwater, and sustain institutional controls. Further, concerns about site protectiveness and integrity and future technological development or future land-use changes may lead to changes in the selected remedies. By 2020, some in place remedy components and controls may need to be replaced or repaired.

There is not only an obligation for the United States to seek solutions to the legacy nuclear waste sites, there is the potential liability costs—which are enormous—of the environmental impacts from long-lived radioisotopes associated with prior activities. In addition to health physics and radiological-protection research in this area, knowledge of the fate and transport of these radioisotopes in the environment, and the underlying chemistry of these processes, are critical needs for defraying future costs of such cleanup and for accurately assessing optimal remediation strategies.

RESEARCH AND EDUCATIONAL OPPORTUNITIES

There are a few advantages of EM in attracting scientists into the nuclear and radiochemistry workforce. First, protection and cleanup of the environment and green chemistry in general appeals to many students. Second, the EM legacy sites are complex and are challenged by interdisciplinary problems (between biological, chemical, geological, and physical processes) that naturally attract the intellectual interest and curiosity of students entering the workforce. The complexity of the EM legacy problems can often be compared to forensic analyses, which is a field that also attracts significant student interest. In this way, EM can act as a unique complement to other nuclear and radiochemistry fields in terms of career options. Third, unlike national security, there are no citizenship restrictions on personnel in the EM field. It is possible that the complementary nature of EM work to nuclear forensics work could be used to train or employ nuclear and radiochemists for most of their day-to-day career responsibilities, making them available during times of national need as part of a large trained response workforce.

Just as there are many radioisotopes of interest in EM, there are a wide variety of open research questions within the field with opportunities for both future funding and for student research projects. Because the EM field is so interdisciplinary, there are also cross-disciplinary implications of the work performed with the potential for broad impacts in other research areas. As an example of the broader impact of this type of research, there is the clear connection between legacy cleanup of previous nuclear activities and the long-term storage of nuclear waste. Since nuclear power has been and will continue to be an important part of the energy equation for the needs of the United States for the foreseeable future, there are critical questions about waste disposal that can be addressed only by further research on the past interaction of nuclear materials with the environment. Just as the research on the Oklo-Okélobondo natural reactors—natural fission reactors in Gabon, west central Africa—have led to critical design parameters for a national underground waste storage facility, current research into rapid and inexpensive radioisotope separations could transform the issue of which radioisotopes can be separated for disposal (de Laeter et al. 1980; Gauthier-Lafaye 2002).

This type of nuclear and radiochemical research will also potentially transform the nuclear fuel reprocessing cycle and, if the harvesting of useful isotopes (such as ^{99m}Tc) from spent fuel is ever permitted, more research into the nuclear and radiochemical methods of separation will be needed in order for practical extraction to routinely occur. The cost savings for developing this type of radiological separation technology are likely to be enormous and there are potential impacts on other fields—especially nuclear medicine—if separated radioisotopes of interest were available as a result of the developed methods.

Another example of the cross-disciplinary impact of research in EM is the recent re-estimation of the neutron dose-response curve of the Hiroshima bomb. This was accomplished using accelerator mass spectrometry measurements of ^{63}Ni and was conducted as part of a basic nuclear and radiochemistry research initiative (Straume et al. 2005). The impact of this EM research was a global re-estimation of the radiation risk assessment and a much higher confidence in the potential health impacts of fast neutron exposure. In this way, fundamental research in EM impacted the health physics and radiological protection fields.

There is also the recognized need for the capacity to analyze and interpret a large-scale radiological event correctly. Although this is unlikely to occur frequently, the workforce and equipment needs to analyze even a single event are likely to be large, for example, based on recent experiences at Fukushima. Even though the earthquake and tsunami occurred in northern Japan, the resulting radiological assessment has involved over 200 people just from DOE offices and laboratories, various universities, and individual consultants since the event occurred (Kelly 2011). If such an event were to occur in the United States, the ability of the nation to respond quickly and appropriately could be severely limited without a significant nuclear and radiochemical workforce that is well trained in the analytical detection and characterization of radioisotopes in the environment. While these measure-

TABLE 7-1 U.S. Department of Energy Environmental Management Research Funding, Office of Technology Innovation and Development (EM-30) for the Past 6 Years

FY	Environmental Management Programs	Total $ for Research	% Invested at Universities	# of Ph.D.s Supported in Pipeline	# of MAs Supported in Pipeline	# of BSs Supported in Pipeline
2005	OTID, FIU	65.9M	11.7%	—	—	—
2006	OTID, FIU	29.05M	0% (carryover)	5	11	4
2007	OTID, FIU	23.72M	12.6%	1	15	10
2008	OTID, FIU	23.56M	12.6%	6	19	10
2009	OTID, FIU	35.4M	11.6%	6	21	10
2010	OTID, FIU CRESP	27.5M	40.2%	20	47	31

ABBREVIATIONS: CRESP, Consortium for Risk Evaluation with Stakeholder Participation; FIU, Florida International University; and OTID, Office of Technology and Innovation Development.
SOURCE: OTID (Office of Technology and Innovation Development; EM-30) input for the tables in this document was received from Pacific Northwest National Laboratory, Oak Ridge National Laboratory, Savannah River National Laboratory, FIU, and Consortium for Risk Evaluation with Stakeholder Participation (CRESP) in FY 2010 (Mary Neu, DOE, personal communication, July 2011).

ments and subsequent data analysis will undoubtedly be the responsibility of national laboratories, a critical workforce shortage in nuclear and radiochemistry and the expected load on the sub-contracted private radioanalytical laboratories will negatively impact the nation's ability to respond to such a situation effectively.

One critical issue in the area of EM, however, is the need for consistent funding of research and development (R&D). The R&D funding for DOE-EM Office of Technology Innovation and Development (OTID) has been inconsistent over the past decade, as indicated below in Table 7-1. Perhaps because it might be deemed less urgent than nuclear security or energy, DOE research and development funding for EM has been periodically cut in a drastic manner. This inconsistency could have detrimental consequences for graduate level research and education, since it is difficult to support a graduate research program when funding is discontinued for a year or more (for example, as it was in 2006). It is both difficult to retain students in the pipeline at a graduate level and hard to attract university personnel into the field without the promise of grant funding opportunities.

WORKFORCE CONSIDERATIONS

As described in the following sections, EM scientists will continue to be employed in four main areas—as federal employees in U.S. Department of Energy facilities and national laboratories, in private radioanalytical laboratories, state regulatory offices, and academic institutions. Much of the radiological monitoring work involves B.S.-level employees with nuclear and radiochemistry training in EM, but there is also a need for Ph.D.-level scientists to retain and expand the knowledge base in the discipline and to educate future generations of scientists that could enter this field. It is projected that a significant number of new nuclear and radiochemists will be needed to fulfill these workforce needs, as detailed below. In some cases scientists from other disciplines are cross-trained to perform radiochemical separations and analytical measurements. Foreign-trained scientists are also hired to help fulfill EM needs.

Department of Energy

In the area of EM, DOE relies on scientists and staff members in national laboratories and other contractor organizations to manage the legacy waste problems created by DOE activities, involving the production of defense nuclear materials and other operations at the DOE sites. The remediation and cleanup of these areas require individuals with expertise in nuclear and radiochemistry, along with knowledge in the geosciences, biological sciences, materials sciences, and various areas of engineering.

Current workforce data for the DOE national laboratories is summarized in Chapter 2 (Figure 2-5). DOE-EM provided numbers for the current level of support for nuclear and radiochemists engaged in its specific mission (see Table 7-2), but does not include the larger BS-level contractor-based cleanup site personnel.

For the national laboratories, most of their effort in EM is focused on research and development that supports cleanup and legacy management activities. Consequently, the national laboratory workforce is composed of primarily Ph.D. scientists in nuclear and radiochemistry, with additional workers at the M.S. and B.S. levels. These national laboratory staff members include both scientists and engineers. Because of the multi-purpose nature of the DOE national laboratories, staff members are often supporting multiple DOE missions. For example, it is likely that an individual nuclear or

TABLE 7-2 U.S. Department of Energy Environmental Management Nuclear and Radiochemical Workforce Estimates for 2011 (does not include clean-up site contractors)

National Laboratories			Non-national Laboratories		
Ph.D.	M.S.	B.S.	Ph.D.	M.S.	B.S.
135	54	23	4	6	3

SOURCE: Mary Neu, DOE, personal communication, July 2011.

TABLE 7-3 Estimation of Future Nuclear and Radiochemistry Workforce Needs (new hires) for the U.S. Department of Energy Environmental Management Over the Next 5 Years (does not include clean-up site contractors)

National Laboratories			Non-national Laboratories		
Ph.D.	M.S.	B.S.	Ph.D.	M.S.	B.S.
118	49	19	6	11	4

SOURCE: Mary Neu, Department of Energy, DOE, personal communication, July 2011.

radiochemistry staff member supports EM in addition to other areas such as nuclear energy or nuclear security.

A unique aspect of the DOE-EM mission compared to other areas of DOE, such as national security, is that work is not just carried out by contractor organizations at national laboratories. For example, Hanford, Oak Ridge, and Savannah River Site are large remediation sites affiliated with but not run by national laboratories; other sites such as Portsmouth and Paducah have large cleanup operations and no associated national laboratories (DOE 2010).

An estimation of future U.S. workforce needs has also been provided by DOE EM in Table 7-3, indicating continued need for expertise in this area.

State Regulatory Agencies and Laboratories

In the area of EM, every state in the United States has at least one state-level agency responsible for radiation control within the state that interface with the U.S. Nuclear Regulatory Commission, as listed in the Directory of Agreement State and Non-Agreement State Directors and State Liaison Officers (USNRC 2011). For example, Massachusetts lists two organizations: the Department of Public Health and the Emergency Management Agency. These agencies vary in size depending on the extent of federal, state, or private enterprises within the state that use radioactive materials. Even states with no active programs or businesses that involve or utilize radioactive materials have state agency personnel that monitor compliance issues associated with naturally-occurring radioactive materials such as radon.

For states with extensive EM needs in the nuclear and radiochemistry, the workforce includes both non-laboratory personnel involved in the policy and assessment of regulatory compliance, and laboratory personnel who are typically radioanalytical chemists completing analyses on environmental samples. In some instances, states hire laboratory personnel to work in state-funded laboratories. In other cases, the radioanalytical work is contracted out to third-parties such as private or academic radioanalytical laboratories. For states with extensive activities, the range of educational levels extends from Ph.D. to B.S., and there may be several employees with nuclear and radiochemistry expertise who work on EM issues. Given the more than 50 state agencies and laboratories in the United States that are concerned with radiological protection and monitoring, there are likely many workers employed with nuclear or radiochemistry skills in this area beyond the 80 state agency representatives mentioned above; however, the committee was not able to determine the number and degree level of those workers and thus did not include this information in its nuclear and radiochemistry workforce estimates. However, an estimate of workforce needs for regulatory agencies with authority over nuclear power plants and U.S. NRC employees is included as part of the demand for nuclear and radiochemistry expertise in nuclear energy and power generation sector discussed in Chapter 5.

Commercial Radiochemistry and Radioanalytical Laboratories

Demonstration of compliance with environmental regulations is required for all entities working with radioactive materials. This includes state-level agencies, DOE EM-funded programs, DOE and the Department of Defense nuclear security programs, the civilian nuclear power enterprise, as well as medical facilities and research laboratories. This demonstration of compliance relies in part upon the collection of environmental samples and the analysis of those samples using radioanalytical chemistry. Private commercial laboratories provide the analysis of such samples as a paid service. The size of the workforce in this sector must be quite large, but it was difficult for the committee to accurately estimate the demand.

Since most of the work conducted by commercial radioanalytical laboratories involves following strictly defined protocols, most of this workforce is composed of B.S.- or M.S.-level chemists working as technicians.

The continued need to comply with regulatory requirements will drive the need for sampling and chemical analysis, making it is reasonable to expect that the workload for commercial radiochemistry and radioanalytical laboratories will continue, if not, increase in the future. Since commercial laboratories tend to rely on general physical and biological scientists at the B.S. level, additional on-the-job training is provided specifically in radiochemistry and radioanalytical chemistry. There will also be some need at the M.A. and Ph.D. levels to provide continued on-the-job training for the private sector.

FINDING

There is a critical need for nuclear and radiochemistry expertise for EM. There will be a continuing need in EM for the foreseeable future due to DOE responsibilities for cleanup and management of its legacy sites, as well as for state regulatory and public health needs. Much of the radiological monitoring work involves B.S.- and M.S.-level employees with nuclear and radiochemistry training in EM, but Ph.D.-level scientists are needed for higher level state and regulatory functions, to retain and expand the knowledge base in the discipline, and to educate future generations of scientists that could enter this field. In the absence of accurate estimates for all EM sectors, the committee conservatively estimates the current and projected EM workforce (in combination with national security needs) to be at a minimum those provided for the national laboratories, shown in Figure 2-5 and Table 2-4.

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8

Summary of Supply and Demand for Nuclear and Radiochemistry Expertise

This chapter presents the committee's summary of estimates of current and projected supply and demand for nuclear and radiochemistry expertise based on the information discussed in the previous chapters. The committee was conservative in its estimates, not wanting to overestimate a need that might result in an oversupply of expertise. Thus, these estimates are, for the most part, based on a status quo in demand. The projected numbers account for anticipated growth in nuclear medicine, but not for any sizable increase in demand in other sectors—as might be needed for a significant expansion of nuclear power or response to a large-scale radiologic release event on US soil.

DEMAND

Based on educational degree data collected from industry, national laboratories (Figure 2-5), and academia (Figure 3-4), the committee estimates that there are currently 416 B.S., 256 M.S., and 765 Ph.D. nuclear and radiochemists employed (Table 8-1).

Over the next five years, due to anticipated retirements and growth in medicine, the committee estimates a need for the hiring of an additional 200 B.S.-, 93 M.S.-, and 306 Ph.D.-level nuclear and radiochemists (Table 8-2).

SUPPLY

The committee assessed current nuclear and radiochemistry academic programs (Chapter 3) to estimate the number of degree holders that would be available to meet the projected demand. As discussed in Chapter 3, there will be approximately 500 B.S. chemistry degree holders and 100 M.S. degree holders per year from departments with two or more nuclear and radiochemistry faculty members (Table 3-3). Of those, approximately

TABLE 8-1 Estimated Number of Currently Employed Nuclear and Radiochemists by Sector and Degree

Sector	B.S.	M.S.	Ph.D.
Medicine*	89	43	163
Energy†	160	49	46
National laboratories (security and EM)	167	164	494
Academia (chemistry faculty only)**	n.a.	n.a.	62
Total	416	256	765

EM, environmental management; n.a., not applicable.

*Includes industry, National Institutes of Health, and nuclear medicine faculty members.

†Includes nuclear and radiochemistry expertise at nuclear power plants, nuclear vendors and support industry, and federal and state regulatory agencies.

**Does not include all staff involved in maintaining nuclear facilities, such as those enforcing safety.

SOURCE: Based on personal communication from industry, national laboratories, and state agencies, and the current number of academic faculty (Figure 3-4).

TABLE 8-2 Estimated Number of Nuclear and Radiochemists to be Hired in the Next 5 Years, by Sector and Degree, to Meet Status Quo Demands

	B.S.	M.S.	Ph.D.
Medicine*	26	20	46
Energy†	104	14	11
National laboratories (security and EM)	70	59	228
Academia (chemistry faculty only)**	n.a.	n.a.	21
Total	200	93	306

EM, environmental management; n.a., not applicable.

*Includes only industry.

†Includes nuclear and radiochemistry expertise at nuclear power plants, nuclear vendors and support industry, and federal and state regulatory agencies.

**Based on number of new faculty since 2009, shown in Figure 3-4.

SOURCE: Based on personal communication from industry, national laboratories, and state agencies, and from recent hires of academic faculty (Figure 3-4).

50 B.S. and 10 M.S. will likely have taken an advanced course in nuclear and radiochemistry. Thus, the projected supply of B.S.-level nuclear and radiochemists over five years is 250 and M.S.-level is 50. Both of these groups would also supply those who enter Ph.D. programs.

Although, as explained in Chapter 1, advanced degrees in nuclear and radiochemistry are no longer tracked by government surveys, the committee was able to identify recent Ph.D.s granted in nuclear and radiochemistry by looking at published theses with nuclear chemistry as a subject keyword: an average of 13 Ph.D. theses per year were published in 2004-2010 (Figure 2-1). If this trend continues and if most of these Ph.D.s remain in the United

TABLE 8-3 Supply and Demand of Nuclear and Radiochemist Degree Holders over the Next 5 Years

	B.S.	M.S.	Ph.D.
Demand	200	93	306
Supply*	250	50	65

*New degree holders

SOURCE: Demand data from Table 8-2; supply data from analysis of academic degrees in Chapter 3.

States (e.g., as U.S. citizens or permanent residents), the projected supply of new Ph.D. nuclear and radiochemists over 5 years is estimated to be 65.

Table 8-3 compares the projected supply and demand for nuclear and radiochemistry degree holders 5 years from now: the projected supply of B.S. chemists seems adequate to meet the projected demand, but the number of Ph.D.s is far short of the projected need of 306 Ph.D.s.

FINDINGS

Estimates of the adequacy of the supply of nuclear and radiochemists to meet future needs are very uncertain, in part because of the difficulty in tracking availability of expertise, as discussed in Chapter 1. For example, there are no specific nuclear and radiochemistry undergraduate degree programs, so the projected supply will be drawn from B.S.-degree chemists who may or may not have specialized expertise in nuclear and radiochemistry. The future pool of Ph.D.s with nuclear and radiochemistry expertise is similarly difficult to estimate because of the lack of data on individuals earning doctorates in these fields and the degree to which other disciplines such as nuclear engineering, inorganic chemistry, and analytical chemistry can serve as “substitute producers” of nuclear and radiochemistry expertise with on-the-job training in the respective application areas.

The committee concludes that the current demand for nuclear and radiochemistry is barely being met by the supply—and on an ad hoc basis at that. Although there is evidence that the number of Ph.D.s in nuclear and radiochemistry is growing, their influx into the pipeline may be insufficient, given the aging of the current workforce with the necessary expertise and the fact that there are limits to the extent to which on-the-job training of those in closely related fields can suffice. For example, many Ph.D.-level nuclear and radiochemists at the national laboratories are inorganic chemists who have been trained on the job. Such training fills gaps in expertise in the short term but does not provide the same quality of preparation and expertise as that of a Ph.D. specifically in nuclear and radiochemistry. Considerable efforts are necessary to sustain the quantity and quality of nuclear and radiochemistry degree programs to ensure an adequate supply of expertise to meet the projected demand.

Based on these findings, the committee provides recommendations in Chapter 10 for action in three main areas: institutional (structural support and collaboration), educational (on-the-job training and knowledge transfer and retention), and collection and tracking of workforce data.

9

Approaches to Assuring U.S. Nuclear and Radiochemistry Expertise

As discussed throughout this report and in past studies, the supply of nuclear and radiochemists has been tenuous for many years. There have been efforts over the past several decades to sustain or increase the number of students and faculty in nuclear and radiochemistry, and nuclear science and engineering as a whole, to support the workforce demands. In this chapter, the committee looks in detail at some of the programs at the undergraduate, graduate, and postgraduate and research levels and evaluates the salient features and adequacy of those efforts to assure current and future needs for nuclear and radiochemistry expertise. The programs are also summarized in Tables 9-2, 9-3, and 9-4. In addition, the committee considers aspects of on-the-job training efforts largely implemented in industry to meet the demand for nuclear and radiochemistry expertise.

NUCLEAR CHEMISTRY SUMMER SCHOOLS

Earlier reports have recommended a number of efforts be undertaken to sustain academic programs in nuclear and radiochemistry.[1] One of the first initiatives that sought to attract and retain new undergraduate student interest in the field of nuclear and radiochemistry that still exists today are the Nuclear Chemistry Summer Schools (see Box 9-1). The summer schools have introduced undergraduate students to nuclear and radiochemistry and provided information on graduate education and on possible careers in these fields. Out of 167 graduates of the San José State University (SJSU) summer school (who attended in 1997-2010) 130 students or 77 percent of graduates went on to attend graduate, medical, or law school. In addition, 42 students or 25 percent of graduates chose to study in either nuclear chemistry or nuclear engineering in graduate school.

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[1] See Chapter 1.

BOX 9-1 NUCLEAR CHEMISTRY SUMMER SCHOOLS

For nearly three decades, the U.S. Department of Energy (DOE) has funded the American Chemical Society Division of Nuclear Chemistry and Technologies (DNCT) Summer Schools in Nuclear and Radiochemistry, first started at San José State University (SJSU) in 1984 with a second one added at Brookhaven National Laboratory (BNL) in 1989 (Clark, 2005; Kinard and Silber, 2005; Peterson, 1997;). The driver for creating the summer schools arose in the late 1970s from concerns about the declining graduate student and faculty population in nuclear chemistry. Initial funding levels were enough to cover student housing and travel, staff and teaching assistant salaries, and some modest costs for guest speakers. Today, funding also covers some student stipends, which is necessary to keep the summer schools competitive with other, more recent summer programs. However, many individuals, including staff and guest speakers, still donate many hours of time and effort to hold the summer schools each year.

Frank Kinard, College of Charleston, provided the committee with an overview of the summer schools. At each location, the summer school is a 6-week intensive program, limited to 12 U.S. citizen undergraduate students (mainly, but not limited to, chemistry majors). Between 1984 and 2010, there have been 577 graduates of the program (321 at SJSU and 256 at BNL). The coursework includes both lectures and laboratory work, and covers fundamental aspects of nuclear and radiochemistry as well as applications such as in medicine, forensics, or environmental management. In 2010, Kinard conducted an extensive survey of SJSU summer school graduates (1997-2010; shown below), in which he determined that 100 graduates out of 167 total when on to attend graduate school. He also found that 35 out of those attending graduate school were in nuclear and radiochemistry fields (Frank Kinard, College of Charleston, personal communication, November 9, 2011). Further information about graduate schools attended is listed below.

Graduate School Choices of SJSU Students (1997-2010)

Graduate School	Total Students	Nuclear Focus
Berkeley	11	7
Washington State University	8	6
Michigan State	6	6
Texas A&M University	5	5
Washington University, St. Louis	5	1
Missouri	3	3
Wisconsin	3	1
Maryland	2	2
Nevada, Las Vegas	2	2
Chicago	2	1
North Carolina State University	2	1
SUNY - Stony Brook	2	1

BOX 9-1 Continued

Through participating in the summer schools, students:

1. Receive fellowship to cover all costs, including a stipend (added in 2005), transportation, tuition, books, and room and board.
2. Cover coursework grounded in fundamentals of nuclear and radiochemistry.
3. Experience hands-on laboratory learning in an American Chemical Society accredited chemistry degree program.
4. Get exposure to a variety of nuclear science applications and practitioners.
5. Interact one-on-one with instructors and guests.
6. Learn from guest lecturers.
7. Visit nuclear science sites.
8. Receive college or university course credit (6-7 units).
9. Receive career guidance and support.

DOE's Office of Basic Energy Sciences (BES) renewed the latest 5-year summer schools grant starting March 1, 2007, which included contributions from the Office of Biological and Environmental Remediation (BER) and Office of Nuclear Physics (NP). The programs held during the summer of 2011 were the last committed under the renewed grant. At the time of this publication, a funding decision had not been made about the grant renewal. The approximate budget is $500,000 total per year for the two summer schools, which includes student housing and participation, course materials and supplies, guest lecture travel, student symposia, field trips, professional development, staff salaries, and space and support charges.

FEDERAL EDUCATIONAL AND FUNDING PROGRAMS

U.S. Department of Homeland Security

National Nuclear Forensics Expertise Development Program

The role of the U.S. Department of Homeland Security's Domestic Nuclear Detection Office (DNDO) in supporting the nuclear and radiochemistry workforce was mandated in the 2010 Nuclear Forensics and Attribution Act, which focused on "maintaining a vibrant and enduring academic pathway from undergraduate to postdoctorate" for national technical nuclear forensics (TNF)-related specialties (including radiochemistry, geochemistry, nuclear physics, nuclear engineering, materials science, and analytical chemistry) through creation of a National Nuclear Forensics Expertise Development Program.

Prior to establishing this program, DNDO commissioned an independent expert panel to address the deficiency in the pipeline for TNF experts (Nuclear Forensics Science Panel Education Sub-Panel 2008). The panel recommended the creation of a "university-national laboratory education program for nuclear forensics," and highlighted critical skill sets to include in the program. The panel also set success metrics for the program, which included training at least 35 new Ph.D. scientists in nuclear forensics-related disciplines over the next 10 years, and suggested that at least 3 to 5 universities and 6 to 7 national laboratories should participate in the program (metrics were echoed by an independent 2008 American Association for the Advancement of Science/American Physical Society nuclear forensics report) (APS/AAAS 2008; Kentis 2011). DNDO reported to this committee that it is making progress to date on increasing Ph.D.-level TNF expertise, with 15-20 graduate fellows and 15 post-doctorates expected to complete the program by FY 2015, and 11 laboratories and 19 participating universities (Kentis 2011). Funding for the program is expected to continue through at least FY 2017 (Samantha Connelly, DNDO, personal communication, April 2012). Brief descriptions of the different initiatives under the program are described below and in Tables 9-2, 9-3, and 9-4 based on updated information received from DNDO (Samantha Connelly, DNDO, personal communication, April 2012).

Nuclear Forensics Undergraduate Summer School

- This six-week program, hosted by a partnership of universities and national laboratories that rotates each year, is modeled after the DOE-sponsored summer schools, which seek to attract undergraduate students to pursue graduate studies in the field. Through "a series of lectures, laboratory experiments, field trips, and practical exercises" this summer school provides students with "a comprehensive, experimental, hands-on training curriculum in topics essential to nuclear forensics."

Nuclear Forensics Undergraduate Scholarship Program

- This is a 9-to-12 week program for undergraduate students to perform forensics-related research at national laboratories. Under the guidance of a senior laboratory mentor and a university faculty advisor, students gain hands-on laboratory experience, produce a scientific report, and deliver an oral presentation of their research upon completion of the program.

Glenn T. Seaborg Institute Nuclear Science Summer Internship Program

- This program funds graduate students and outstanding undergraduate students, through support from DNDO, to perform nuclear forensics related research at Lawrence Livermore National Laboratory and Los Alamos National Laboratory during the summer. DNDO works closely with the participating laboratories to guide selection of nuclear forensics related projects.

Nuclear Forensics Graduate Fellowship Program

- This DNDO program, in partnership with the Defense Threat Reduction Agency, provides tuition and stipend support to graduate students pursuing doctoral degrees in nuclear, geochemical, and related disciplines at approved universities. During the program, students must maintain a consistently high-level academic standing and conduct two, 10-week laboratory internships in approved facilities. Upon graduation, fellows must serve for two years in a post doctoral or other staff position in a technical nuclear forensics-related specialty at a DOE or DOD laboratory, or a federal agency.

Post-doctorate Fellowship Program

- This program provides three-year postdoctoral fellowships at national laboratories to encourage recent Ph.D. graduates with relevant technical expertise to enter the nuclear forensics workforce.

Nuclear Forensics Junior Faculty Award

- This program provides funding for up to three years to tenure-track faculty (with less than six years experience at the time of application) to cover salary and travel to national laboratories to perform nuclear forensics-related research, to facilitate research and development projects, and to purchase equipment. Universities are encouraged to provide partial matching funds.

Nuclear Forensics Education Award

- In partnership with DOE's National Nuclear Security Administration (NNSA), this program awards grants to colleges and universities to support many activities, including development of nuclear forensics curriculum, hiring of faculty, and constructing new on-site facilities. The awards are cost-shared grants, renewable for up to three years, to support educational programs in analytical, geological, and radiochemistry, nuclear physics and engineering, and materials science.

U.S. Department of Energy

In addition to the long-term support for the nuclear chemistry summer schools, the DOE Office of Science has also provided long-term support for basic research, especially for the Heavy Element Chemistry Program (Table 2-5). Other DOE programs and national laboratories also have programs that support nuclear and radiochemistry, as described below.

Nuclear Energy University Programs

Since 2009, Nuclear Energy University Programs (NEUP)—a program initiated by the DOE Office of Nuclear Energy—has provided $167 million of funding for nuclear science and engineering research and education to 75 universities in 35 states, including $121.4 million in research projects (Table 9-1). The FY 2012 plans that were announced by DOE Nuclear Energy Assistant Secretary Lyons on August 9, 2011, did not include scholarships and fellowships (DOE 2011a). Funding provided by NEUP includes several awards described below:

University Research and Development Awards

- “NEUP seeks to align the nuclear energy research being conducted at U.S. colleges and universities with DOE’s mission and goals.
- The program is supporting projects that focus on needs and priorities of key Office of Nuclear Energy programs, including fuel cycle,

TABLE 9-1 Nuclear Energy University Program Awards and Funding, FY 2009-FY 2011

Awards	FY 2009	FY 2010	FY 2011
University Research and Development Awards[a]	$44 million 71 awards to 31 schools in 20 states	$38 million 42 awards to 23 schools in 17 states	$39 million 51 awards to 31 schools in 21 states
Integrated Research Projects[a]	N/A	N/A	TBA
University Infrastructure Awards[a]	$6 million 29 schools in 23 states for scientific equipment	$13.2 million 39 schools in 27 states for research reactor upgrades and scientific equipment	TBA
University Student Fellowship and Scholarship Awards	$3.1 million 76 scholarships and 18 fellowships	$5 million (IUP) 85 scholarships and 32 fellowships	TBA (IUP)
Total	$53 million	$56.2 million	Approximately $60 million

ABBREVIATIONS: IUP, integrated university program; N/A, not applicable; TBA, to be announced.
[a] From 20% of the nuclear energy research and development budget.
SOURCE: Gilligan 2011.

reactor concepts, and transformative 'blue sky' research." (DOE 2011b)

Integrated Research Projects

- "Integrated Research Projects (IRPs) are 3-year awards for projects that focus on a specific nuclear energy programmatic area of investigation. The intent of the effort is to engage the university community on larger research projects designed to benefit from the involvement of multiple universities, as well as industry, utility, and national laboratory partners." (DOE 2011b)
- "Proposals may include a combination of evaluation capability development, research program development, experimental work, and computer simulations. Proposals must include a designated lead university and at least one other university, and are encouraged to include one or more industry or utility partner that may receive funding support from the project.
- Proposals may also include one or more national laboratories that may receive project funding support." (DOE 2011c)

University Infrastructure Awards

- Support university and college efforts to build or expand nuclear science and engineering research and education. The NEUP will provide funds to upgrade university-level research reactors and purchase general scientific equipment and instrumentation.

University Student Fellowship and Scholarship Awards

- Fellowships are $50,000 a year over 3 years to help pay for graduate studies and research.

The Institute for Nuclear Energy Science and Technology

Idaho National Laboratory (INL) with funding from the DOE has partnered with several leading U.S. universities to create the Institute of Nuclear Energy Science and Technology (INEST), which has a goal to help INL's long-term nuclear energy research and development strategy. The institute is comprised of five Centers of Research and Education (COREs) that were selected to address some of the most difficult problems facing nuclear energy today: fuels and materials, space nuclear research, fuel cycle, and safety and licensing. Research in these areas will provide the technical knowledge to help guide the nation's nuclear energy program. Each CORE is led by a researcher at INL and one of the partner universities—Massachusetts Institute of Technology, North Carolina State University, Ohio State University, Oregon State University, and University of New Mexico. The intent is to collaborate with universities to stimulate research innovation and maintain INL's position as a leader in nuclear energy research. The mission of the Fuel Cycle CORE is specifically focused on training and education in radiochemistry.

National Analytical Management Program

DOE's Carlsbad Field Office has been tasked by the DOE Office of Environmental Management (DOE-EM) to re-establish the National Analytical Management Program (NAMP), and to create a DOE Environmental Response Laboratory Network Coordination Office. Through NAMP, Patricia Paviet-Hartman of INL is leading the efforts for training and education in radiochemistry and radioanalytical chemistry. Several agencies are participating in the NAMP program, including the U.S. Environment Protection Agency (EPA). Paviet-Hartmann told the committee that she is working on identifying universities and agencies that provide courses in radiochemistry. For example, basic radiochemistry materials have been developed and posted online by the EPA "for chemists and chemical laboratory managers in state health department laboratories who may be required to analyze water samples for the presence of radionuclide contamination" (EPA 2011). According to Paviet-Hartmann, EPA is in the process of developing a more advanced 5-day radiochemistry class. Additional radiochemistry webinars are being developed, several universities are participating: University of Nevada Las Vegas, University of California Irvine, Oregon State University, University of Iowa, Clemson University, University Texas El Paso. The first webinar is anticipated to start in March 2012. She said the goal is to build a library of knowledge accessible to all.

Stockpile Stewardship Program Science Graduate Fellowships

This NNSA program is targeted at "students pursuing a Ph.D. in areas of interest to stewardship (SSP) science, such as high energy density physics, nuclear science, or materials under extreme conditions and their hydrodynamics."

National Science and Security Consortium at Berkeley

In June 2011, the NNSA announced a 5-year, $25 million award to the University of California, Berkeley to establish the National Science and

Security Consortium, a multi-university effort focused on training and education of experts to support DOE's National Nuclear Security Administration nuclear nonproliferation mission. Expertise will include nuclear physics, chemistry, engineering, instrumentation, and public policy. According to the NNSA press release, the Nuclear Science and Security Consortium "will focus on the hands-on training of undergraduate and graduate students in the fields of nuclear physics, nuclear and radiation chemistry, nuclear engineering, nuclear instrumentation and public policy. The consortium's nickname is SUCCESS PIPELINE, which stands for Seven Universities Coordinating Coursework and Experience from Student to Scientist in a Partnership for Identifying and Preparing Educated Laboratory-Integrated Nuclear Experts." (NNSA 2011)

Next Generation Safeguards Initiative

In support of international safeguards administered by the International Atomic Energy Agency (IAEA), which serve to monitor nuclear activities under Article III of the Non-Proliferation Treaty, the NNSA launched this program in 2008 "to promote the strengthening of nuclear safeguards worldwide to help ensure the safe, secure and peaceful implementation of civil nuclear energy programs." (NNSA 2008). One key component of this initiative is the Human Capital Development subprogram, which aims to attract, educate, train, and retain the next generation of international safeguards professionals and encourage U.S. experts to seek employment at the IAEA. Recently, it was projected that more than 80 percent of international safeguards experts at the U.S. national labs will retire in the next 15 years (Whitney et al. 2010).

According to NNSA, "Since 2008, the initiative has sponsored over 350 internship positions at the Laboratories, exposed over 500 university students to safeguards topics through curriculum development and short courses, funded over two dozen post-doctoral and graduate fellowships, supported the transition of new professionals into the nonproliferation workforce through education and training courses, and established a professional network for permanent new safeguards staff" (Sean Dunlop and Robert Hanrahan, NNSA, personal communication, June 1, 2012). Recent opportunities under this initiative include the Nuclear Nonproliferation International Safeguards Graduate Fellowship Program (SCUREF 2012) and Nuclear Nonproliferation, Safeguards, and Security in the 21st Century course at Brookhaven National Laboratory (BNL 2012) for prospective, current, and recent graduate students in the physical sciences, engineering, and international relations.

Integrated Radiochemstry Research Programs of Excellence—Predoctoral and Postdoctoral Program for Radiochemistry Training

In 2009, the U.S. Department of Energy (DOE) Office of Biological and Environmental Research (BER) and the DOE Radiochemistry and Imaging Instrumentation Program issued a call to develop Integrated Radiochemistry Research Programs of Excellence. This call was made in response to one of the recommendations from the National Research Council/Institute of Medicine study on *Advancing Nuclear Medicine Through Innovation* (NRC/IOM 2007). The goals of the program were two-fold, "1) Integrated involvement of graduate-student and postdoctoral trainees in the fundamental research that seeks improvements in radiolabeling and radiotracer development chemistry in the following areas of interest to BER: a) Development of new chemical reactions for high specific activity probe synthesis, b) Models to study reactivity at the tracer mass scale, c) Nanoparticle platforms that can incorporate one or more imaging agents and d) Automation technology for radiotracer synthesis; and 2) Enhancement of training opportunities in radiochemistry to ensure the future availability of human resources for important radiochemistry applications" (DOE 2009). The successful applicants had to describe their multifaceted education and training program combined with radiotracer research training that was relevant to the mission of the DOE Office of Biological and Environmental Research.

Six programs, geographically dispersed across the United States, were selected for the 3-year grants worth $1.8 million. The six programs include Memorial Sloan Kettering Cancer Center (New York), Northeastern University (Boston), University of Missouri Columbia, University of California Los Angeles, Washington University St. Louis (Missouri), and the collaborative University of California, Davis, University of California, San Francisco, and Lawrence Berkeley National Laboratory program. The six programs planned to train 15 or more postdoctoral fellows and 20 or more graduate students. In most cases the postdoctoral fellows will not have received formal nuclear or radiochemistry training as a graduate student, thus bringing in those fellows with varied chemistry backgrounds into the field. The training is intended to be a mixture of didactic coursework and practical laboratory research opportunities. Internships with collaborating laboratories were described and encouraged. The program is just now completing its second year with a few trained individuals emerging from the program.

While the funding for the continuation of this program is uncertain, a fourth year of funding was recently extended to the current centers.

U.S. Nuclear Regulatory Commission Education Programs

Since 2005, the Nuclear Regulatory Commission has provided funding for curriculum development, scholarships, and faculty development. Grants total $20 million—$5 million for curriculum development and $15 million for scholarships and fellowships, faculty development, and trade schools and community colleges—and focus on nuclear engineering, health physics, and radiochemistry. Between 2007 and 2010, the Nuclear Regulatory Commission awarded 313 grants totaling $65 million to 108 institutions in 33 states, the District of Columbia, and Puerto Rico, including support to over 500 students annually.

Seven chemistry-specific grants from 2009 to 2011, totaling $946,962, were identified from the list of awards on the Nuclear Regulatory Commission website (USNRC 2011a). These grants include:

- Two Nuclear Education Curriculum Development Program Awards (FY2011); one to the College of Charleston for enhancement of the undergraduate nuclear and radiochemistry curriculum through the development of radiochemistry laboratory experiments ($56,875), and one to the University of Missouri, Columbia for the development of a course on reprocessing, recycle chemistry, and technology ($124,366).
- One Faculty Development Grant Program Award (FY2011) to the University of Missouri, Columbia for a radiochemistry faculty development program in actinide chemistry ($298,377).
- Two Nuclear Education Curriculum Development Program Awards (FY2010); one to Missouri University of Science and Technology for the creation of a radiochemistry teaching program in nuclear engineering ($125,000), and one to Clemson University for the development of coupled online and hands-on radiation detection and radiochemistry laboratory courses ($163,193).
- Two Nuclear Education Grant Program Awards (FY2009); one to Clemson University for the development of coupled online and hands-on radiation detection and radiochemistry laboratory courses ($89,151), and one to Pennsylvania State University for curriculum development for a radiochemistry education program ($90,000).

ON-THE-JOB TRAINING

In some cases, employers currently fill gaps in need by training nuclear specialists after they are hired. As discussed in Chapter 5, the nuclear power industry recruits almost its entire chemistry workforce from B.S.-level graduates with chemistry and related degrees. However, since the curricula of B.S.-level graduates in chemistry and physics in the United States does not typically emphasize nuclear chemistry or radiochemistry (see Chapter 3), the industry has thus come to expect little or no knowledge in radiochemistry or nuclear chemistry from its applicants, and tends to train its own workforce. An example is the large nuclear reactor-services vendor AREVA, which has 12 training centers in France, Germany, and the United States, with over 500 training programs, more than 100 full-time trainers, and high-capacity training facilities equipped with modern technologies. Its U.S. training center is in Lynchburg, VA (AREVA 2011). In another example, Exelon Nuclear developed a knowledge transfer and retention program to ensure expertise for the company (Box 9-2).

Similarly, national laboratories involved in working on nuclear security and energy often recruit and hire inorganic and physical chemists and materials scientists, mostly at the Ph.D. level, and then train many of them to become nuclear/radiochemistry professionals. For example, Los Alamos and Livermore National Laboratories have developed specialized in-house curricula, such as those of their Seaborg Institutes, to train and mentor nuclear/radiochemistry research staff (Clark 2011). While students may emerge from graduate programs proficient in fundamental nuclear and radiochemistry, evaluation of interdicted material or nuclear debris data is a skill that has to be taught over a period of several years after the worker receives a security clearance. The adequacy of radiochemistry expertise in these programs relies on the effectiveness of knowledge transfer. Historically, the nuclear weapons program maintained a strong level of expertise, giving senior scientists enough time to execute missions, conduct R&D, and train new staff (see Chapter 6). As the weapons programs have changed, support has not always been available for experienced workers to record their knowledge. For example, workers who had experience with underground testing have been lost to retirements and attrition. This is a significant impediment to retaining nuclear and radiochemistry expertise, which could be addressed with a formal knowledge management program as discussed in Box 9-2.

On the other hand, while the work environments, funding mechanisms, and program execution are quite different, much of the knowledge base and critical skills and many of the methods and applications of nuclear and radiochemistry in the environmental management and national security areas are similar. This is particularly true for B.S.-level radioanalytical chemistry

BOX 9-2 KNOWLEDGE TRANSFER AND RETENTION

Exelon Nuclear (Exelon 2011)—a company that owns and operates approximately 20 percent of the nuclear power plants in the United States—identified that a large number of very experienced nuclear workers were eligible to retire within the next 5 years, and thus a process was required to minimize the impact of losing many years of nuclear experience in a short period of time. A detailed project was undertaken during a supervisory develop program class that provided recommendations for the company and led to the development of a corporate procedure to formalize the knowledge transfer and retention process.

In response to the knowledge transfer and retention process developed at Exelon Nuclear, several successful actions were taken over the past 2 years including the following within the chemistry departments:

- At the Exelon Three Mile Island plant, a 30-year radiochemist announced his retirement 1.5 years before his retirement date. The chemistry manager requested and received approval to over hire for the position one full year before the retirement date. The replacement chemist had several years of nuclear experience and during that year shadowed the experienced radiochemist. The experienced radiochemist mentored his replacement and at the end of the time Three Mile Island had a qualified radiochemist with significant knowledge about the history on why things were done the way they were. In another example at Three Mile Island, the reactor chemist announced his retirement and a similar request to over hire was made and approved. A very experienced chemical engineer from the engineering department was selected to shadow the retiring reactor chemist. In both cases at Three Mile Island, this process implemented proved to be a successful model to follow to replace experienced chemists without losing significant knowledge and to allow the plant and the chemistry department to continue to operate at high levels of performance.
- At other stations, the training and qualification of back-up employees is accomplished through a strong succession planning process. This process has been successfully performed at LaSalle and the Quad Cities Stations where degreed chemistry technicians were hired, trained, and qualified. After several years of gaining experience, the technicians were promoted to management in analytical or auxiliary chemist positions. Then after they were qualified and successfully performing at those entry-level chemist positions, they were assigned duties to learn and qualify as a reactor chemist or radiochemist. After becoming fully qualified, they were then rotated into the reactor or radiochemist positions and the radiochemist was promoted into a supervisory position. In these examples, the very experienced reactor chemist or radiochemist became a supervisor within the department and was able to continue to mentor for several years until all knowledge is successfully transferred.

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technicians who analyze environmental samples. Cross-training between these two technical areas provides the opportunity for leveraging the work groups in these two areas to address short-term needs in both areas. This could be especially effective should the national security area require a large-scale rapid response to a specific event and an associated analysis of a large volume of environmental samples.

While each of the initiatives in Tables 9-2, 9-3, and 9-4 has attracted stu-

TABLE 9-2 Undergraduate Academic Pipeline Initiatives and Funding

Program	Year Established	Current Student Participation and Funding	Notes/Description
Department of Homeland Security			
Nuclear Forensics Undergraduate Scholarship Program	2011	5 students per year	9- to12-week summer research internship at a national laboratory at varying locations across the United States (DHS 2010a)
Nuclear Forensics Undergraduate Summer School	2010	10 students per year	4-6 week session hosted by the University of Nevada, Las Vegas (2010), Washington State University (2011), and University of Missouri-Columbia (2012); regional partnership with Los Alamos National Laboratory, Lawrence Livermore National Laboratory, Savannah River National Laboratory, federal interagency partners, and others (DHS 2010b)
Department of Energy			
Office of Science support for Nuclear Chemistry Summer Schools	1984	24 students and $500,000 per year	(see Box 9-1) (ACS 2011)
Nuclear Energy University Programs-University Student Fellowship and Scholarship Awards	2009	$3.1 million, 76 scholarships, and 18 fellowships (FY 2009); $5 million, 85 scholarships, and 32 fellowships (FY 2010) per year	Covers both undergraduates and graduates (DOE 2011b,d);
Idaho National Lab, National Analytical Management Program	2011	TBA	(INL 2011a)
Nuclear Regulatory Commission			
NRC Education Programs	2005	$5 million for curriculum development $15 million for scholarships/ fellowships per year	(USNRC 2011b)

TABLE 9-3 Graduate-level Academic Pipeline Initiatives

Program	Year Established	Current Student Participation and Funding	Notes/Description
Department of Homeland Security			
Glenn T. Seaborg Institute Nuclear Science Summer Internship Program	2008	10-15 students per year	8-10 weeks at Lawrence Livermore National Laboratory, Los Alamos National Laboratory; graduate and outstanding undergraduate students work on critical skills areas related to nuclear forensics (DHS 2010c)
Nuclear Forensics Graduate Fellowship Program (with Department of Defense Defense Threat Reduction Agency)	2008	22 graduate fellows per year	11 laboratories and 19 participating universities throughout the United States Tuition and stipend for 12 months at an approved university, including at least 2 summer internships at a national laboratory and a service payback requirement. Includes mentoring funds (DHS 2010d)
Department of Energy			
Idaho National Lab, Center for Advanced Energy Studies (joint funding from State of Idaho)	2009	FY 2010: 11 scholarships awarded; and attracted 418 students to nuclear engineering and science programs in Idaho universities. FY 2011: expect to hire 275 interns in energy-related fields. $1.6 million annually from State of Idaho; $6 million from DOE for startup and equipment; $15 million INL; $22 million research grants.	Idaho National Lab and three Idaho universities—Boise State University, Idaho State University, and University of Idaho. (CAES 2011)
Idaho National Lab, Institute for Nuclear Energy Science and Technology, Centers of Research and Education	2009	unknown	Idaho National Laboratory with MIT, NC State, Oregon State, Ohio State, and U New Mexico (INL 2011b).
Idaho National Laboratory, National Analytical Management Program	2011	unknown	(INL 2011a)

Continued

TABLE 9-3 Continued

Program	Year Established	Current Student Participation and Funding	Notes/Description
Integrated Radiochemistry Research Projects of Excellence (A new solicitation for Integrated Nuclear Medicine Research Projects of Excellence announced in 2012)	2009	Six programs; $1.8 million; 15 post docs and 20 students each program	Northeastern University, Memorial Sloan Kettering Cancer Center, Washington University St. Louis, University of Missouri Columbia, University of California Los Angeles, and a collaboration with University of California Davis, San Francisco, and Lawrence Berkeley National Laboratory (DOE 2012)
Nuclear Energy University Programs-University Student Fellowship and Scholarship Awards	2009	$3.1 million, 76 scholarships, and 18 fellowships (FY 2009); $5 million, 85 scholarships and 32 fellowships (FY 2010)	Covers both undergraduates and graduates. (DOE 2011b,d)
National Nuclear Security Administration- Stewardship Science Graduate Fellowships	2006	10 alumni, 20 current fellows	Takes place at National Laboratories—Lawrence Livermore National Laboratory, Los Alamos National Laboratory, and Sandia National Laboratory (Krell Institute 2011)
Nuclear Regulatory Commission			
NRC Education Programs	2005	$15 million for scholarships and fellowships per year (undergraduate and graduate level)	(USNRC 2011b)

dents into the field or sustained junior faculty in nuclear and radiochemistry, there is no cohesive or coordinated pattern of support for nuclear or radiochemists. Each of these initiatives works independently from the others, and most were realized recently by the funding organizations as urgent measures to stem the erosion of nuclear and radiochemistry expertise, and the overall effect has been a modest flattening of the curve in terms of the number of Ph.D. students entering the field (see Chapter 2, Figure 2-1). An educational and career pathway that is robust and sustainable ideally needs to draw students into the field at the undergraduate and graduate levels, provide postdoctoral research opportunities, and provide professional career entry opportunities so that the workforce is adequate, yet not oversupplied, for the needs of the nation. When the number of faculty and facilities within a par-

TABLE 9-4 Postdoctoral and University Research Programs

Program	Year Established	Current Student Participation and Funding	Notes/Description
Department of Homeland Security			
Nuclear Forensics Post-doctoral Fellowship Program	2009	12 awards per year	All postgraduate and university awards are geared toward National Technical Nuclear Forensics mission needs. 11 laboratories—Savannah River, Lawrence Livermore, Pacific Northwest, Sandia, NIST, Oak Ridge, New Brunswick, Argonne, Idaho, Los Alamos, and AFIT
Nuclear Forensics Junior Faculty Award Program	2010	6 per year	Faculty institutions are encouraged to provide matching funds and awards are renewable for three consecutive years. Current awardees: University of Michigan, Pennsylvania State University, North Carolina State University, Clemson University, University of Missouri, Columbia University, and sixth award to be announced. (Samantha Connelly, DNDO, personal communication, April 2012)
Nuclear Forensics Education Award Program (with U.S Department of Energy National Nuclear Security Administration)	2009	7 awards	Requires school matching funds and renewable for three consecutive years (Samantha Connelly, DNDO, personal communication, April 2012)
Department of Energy			
Nuclear Energy University Programs	2009	$44 million, 71 awards to 31 schools (FY 2009); $38 million, 42 awards to 23 schools (FY 2010); $39 million, 51 awards to 31 schools (FY 2011)	(DOE 2011 b,d)
National Nuclear Security Administration- National Science and Security Consortium at Berkeley	2011	$25 million over 5 years	University of California, Berkeley; Michigan State University; University of California, Davis; University of California, Irvine; University of Nevada, Las Vegas; University of California Institute on Global Conflict and Cooperation in San Diego; and Washington University at St. Louis (NNSA 2011)

ticular discipline become so few as in nuclear and radiochemistry, a coherent and consistent support mechanism between the various stages of a student's career in academia is essential to ensure the availability of strong university programs with multiple faculty members and advanced coursework.

In addition, not every nuclear or radiochemistry-related position in industry will require a Ph.D.-level nuclear or radiochemist—that is, the demand in industry includes the need for nuclear and radiochemistry staff at the B.S. and M.S. levels as well as Ph.D.s. As discussed earlier, many current positions are being filled by on-the-job cross-training of professionals in other related disciplines (such as nuclear physics, health physics, and physical and inorganic chemistry), as well as cross-training and transition into the field by working professionals. The committee recognizes that these cross-training entry points are important for meeting the current and future needs and are beneficial in introducing new perspectives and experiences; however, the health of the field also demands the depth of commitment of those who devote their entire careers to the discipline. For example, professionals trained in other disciplines are unlikely to become faculty in university settings that produce future Ph.D. students in nuclear and radiochemistry. While it is necessary to meet the impending shortages of trained personnel, it will not be possible to sustain or regrow a discipline in this manner. As indicated earlier, the academic pipeline in nuclear and radiochemistry is, at best, at a plateau of nuclear chemistry faculty and graduates. Given the increased demand in many sectors such as nuclear medicine and nuclear energy, this steady but low number of graduates in nuclear and radiochemistry is not conducive for sustained growth of the field.

INTERNATIONAL EFFORTS

The committee evaluated education and training in nuclear and radiochemistry in comparable foreign countries, specifically the United Kingdom and France.

United Kingdom

Declines in nuclear research activity have also taken place in the United Kingdom as noted in a presentation to the committee by Francis Livens, professor of radiochemistry at the University of Manchester, United Kingdom (Livens 2011). Personnel in nuclear fission research has declined over the last 25 years, as shown in Figure 9-1, with the privatization of the major government funded entities British Nuclear Fuels Limited (BNFL) and the United Kingdom Atomic Energy Authority (UKAEA), and the dissolution of

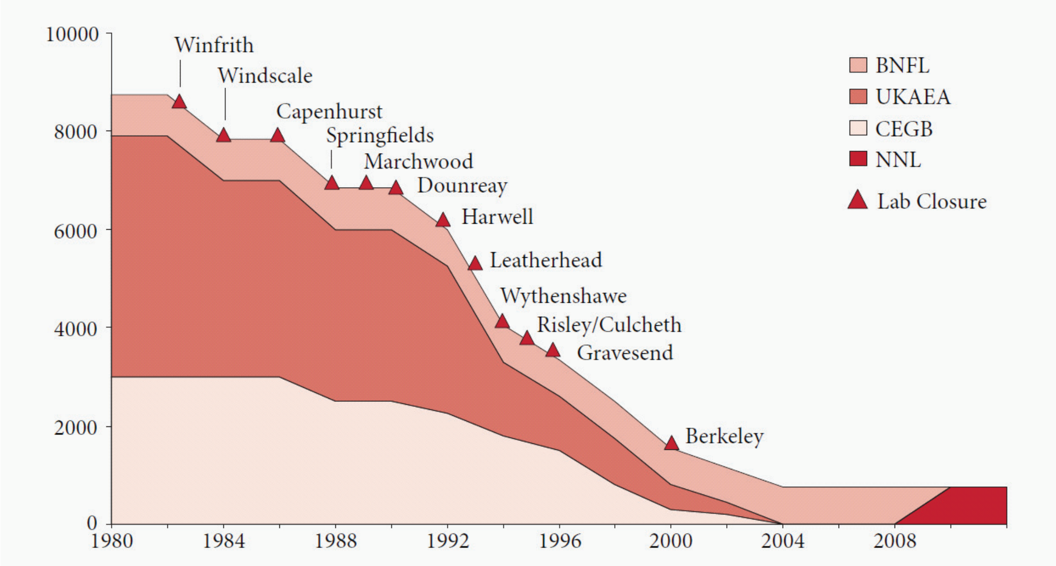

FIGURE 9-1 Decline in United Kingdom civil research and development personnel.
Abbreviations: BNFL, British Nuclear Fuels Limited; CEGB, the Central Electricity Generating Board; NNL, National Nuclear Laboratory; UKAEA, United Kingdom Atomic Energy Authority.
SOURCE: House of Lords 2011.

the Central Electricity Generating Board (CEGB) in November 2001. Even without new nuclear efforts, industry needs 1,000 graduates per year (B.S. and above) including many chemists; 700 to replace retirements and 300 to support growth in waste management and site restoration (HC 2009). Livens described a series of policy decisions the U.K. government made over the last 10 years to reverse the negative trend.

The Centre for Radiochemistry Research (CRR) was created in 1999 with support from BNFL. It is the first of four BNFL university research alliances. Livens is currently research director of the Dalton Nuclear Institute at the University of Manchester, of which the CRR is a constituent. The CRR has an annual operating budget of about £2.8 million, which supports four full-time academic staff, 8 postdoctoral fellows and 23 Ph.D. students in chemistry, and leads the Engineering and Physical Sciences Research Council-funded Fission Doctoral Training Centre (DTC). According to Livens, there are now more than 50 CRR alumni working in the nuclear industry. CRR facilities include:

- Radiochemistry labs allowing the use of technetium (Tc), neptunium (Np), plutonium (Pu); (up to 100 mg Np or 10 mg ^{242}Pu);
- Radiochemical detection and counting facilities for measurement of alpha, beta, and gamma emissions;
- Radiochemical separations for low-level analysis; and
- Access to equivalently equipped or appropriately equipped facilities in the United Kingdom, Europe, and the United States.

One of the key expectations of the Fission DTC in terms of workforce development is to recruit 10 doctoral students per year who will receive specific coursework in nuclear and radiochemistry and who will work on challenging Ph.D.-level research projects. The 12 weeks of instructional material covers topics such as the atomic nucleus, the nuclear fuel cycle, reactor systems, nuclear fuels, materials, radioactive waste management, and multiscale modelling. The Ph.D. supervisors for the Fission DTC program are drawn from a pool of over 30 academic faculty members. Ph.D.s must be co-supervised, preferably across disciplines and institutions. The first two igroups of students in the program included six chemists, four engineers, six physicists, and five earth and environmental scientists. Livens said the next steps are uncertain. Possibilities include creating a national nuclear laboratory, and extending the Fission DTC model across the United Kingdom.

The French Educational Model

While the United States generates more nuclear power than any country in the world, France has the largest worldwide percentage of its electricity from nuclear power (78 percent). The large nuclear power industry drives much of the education efforts in France.

There are six French universities with "radiochemistry groups"—Nantes, Montpellier, Strasbourg, Lyon, Nice, and Paris-Sud. Each university has six to twelve permanent research-teaching staff. The largest group, Paris-Sud, has a two-year "nuclear energy" international M.S. program. Approximately 25 students follow the "radiochemistry/fuel cycle" master's-level specialty at Paris-Sud each year (Eric Simoni, Paris-Sud, personal communication, June 23, 2011).

The French academic sector is represented by university faculty as well as parallel researchers with "habilitation"[2] degrees at the French Alternative

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[2] "Habilitation" is an academic degree in Europe that is above a Ph.D. and that is a prerequisite to university-level teaching and research. It requires independent research and a thesis defended before oral examiners.

Energies and Atomic Energy Commission (Commissariat à l'Énergie Atomique et aux Énergies Alternatives, CEA) and other institutions. Curricula at the six French universities with radiochemistry-groups include nuclear chemistry and radiochemistry.

Engineering education in France follows a different path. Students follow a 2-year preparatory program, then enroll in one of the many French engineering institutes—that is, Grandes Écoles d'Ingénieurs, for example École Polytechnique and École des Mines in Paris—to pursue a 3-year general master's degree in engineering. Industry and technical institutes then hire master's degree recipients and teach them the required specialized skills (for example, skills in chemical, civil, electrical, and nuclear engineering) to meet company needs. CEA has its own research and training institutes, for example the National Institute for Nuclear Science and Technology (Institut Nationale de Sciences et Techniques Nucléaire) (IAEA 2011).

The nuclear power industry in France is owned and managed by a single government-private entity, Electricité de France (EDF), which is a "Société Anonyme"—that is, a private company that is 85 percent government-owned—with over 150,000 employees. A new French nuclear energy educational initiative—the French Council for Education and Training in Nuclear Energy (Conseil des Formations en Energie Nucléaire, CFEN)—was started in 2008 because the demand for expertise exceeded supply, mostly because of an aging nuclear energy workforce. During the coming decade, French institutions must recruit about 13,000 scientists and engineers with M.S. or Ph.D. degrees and 10,000 B.S.-level science technicians. The French initiative represents a broad focus in nuclear education in the nuclear energy area, including nuclear energy in general (mainly nuclear power) and the nuclear deterrence segment of CEA (Guet 2011).

CFEN was established by the French minister of higher education and research. EDF, CEA, and the large nuclear vendors AREVA and GDFSUEZ participate in CFEN. President Sarkozy has challenged this consortium to develop "Centers of Excellence" in nuclear science to provide the workforce for nuclear power and nuclear deterrence (Sarkozy 2010).

Other International Efforts

There is extensive international collaboration in nuclear science education led by French institutions and European Community institutions. One initiative is ACTINET-I3 (Integrated Infrastructure Initiative for Actinide Science),[3] a consortium of 30 European research organizations from 13

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[3] For more information, see ACTINET 2011.

countries devoted to basic sciences of the actinide elements. Together, the members of ACTINET form a network of actinide facilities that can support each other and also collaborate and conduct joint research activities. For example, ACTINET-I3 held summers schools for students from across Europe in 2010 and 2011 similar to the DOE-sponsored Nuclear Chemistry Summer Schools. In Japan, a parallel national initiative, J-ACTINET, has been launched. ACTINET-I3 serves as an excellent model for U.S.-based partnerships for nuclear and radiochemistry.

FINDINGS

The committee commends the long-term and more recent efforts of federal agencies to support nuclear and radiochemistry workforce education and development. There is some evidence that the recent efforts of the past five years have helped to improve the nuclear and radiochemistry expertise pipeline, at least as reflected in the number of new faculty hired in nuclear and radiochemistry (see Figure 3-4). However, these initiatives have been created separately and independently from each other, usually by different funding agencies with a slightly different emphasis on outcome. There exists a great potential for gaps in funding between the various parts of the academic pipeline, and there appears to be no comprehensive plan in place to address academic pipeline issues in general. It is also uncertain that current funding levels will continue. For example,

- The grant for the Summer Schools in Nuclear Chemistry held at SJSU and BNL is up for its 5-year renewal.
- NEUP made a funding announcement in August 2011 for university research and development awards, but has not yet funded any fellowship and scholarship awards.
- DNDO funding has been planned out to 2018 depending on availability of funding (Samantha Connelly, DNDO, personal communication, April 2012).

Students will be attracted into the nuclear and radiochemistry field by long-term, stable opportunities. Clear funding initiatives at each educational level help to sustain students in the field. There are several educational programs that have been developed over the past few decades that are designed to address pipeline issues in nuclear and radiochemistry. There is some evidence that the most recent efforts during the past five years may indeed have helped to stem the tide, at least as reflected in the number of graduate program faculty (Chapter 3) and Ph.D. students produced in nuclear and radiochemistry (Chapter 2). However these initiatives have been created separately and independently from each other, usually by different funding agencies with a slightly different emphasis on outcome. Also, they have focused more on graduate education and postdoctoral fellowships than undergraduates.

Many federal agencies support a segment of nuclear and radiochemistry professional education and training by means of a summer school or research grants and fellowships. With the exception of small programs within the DOE Office of Science, the National Science Foundation, and some institutes of the National Institutes of Health, these initiatives are usually so specialized that their impact is narrow. Often the initiatives are temporary. A broad and sustained educational focus can best be achieved by coordinated interactions among federal agencies with leadership from a federal research office that has nuclear chemistry and radiochemistry as part of its mission.

On-the-job training plays a critical role in meeting short-term and long-term workforce needs. Since the curricula of most graduates in chemistry and physics in the United States does not typically emphasize nuclear chemistry or radiochemistry (see Chapter 3), many employers currently fill gaps in need by training nuclear specialists after they are hired. Similarly, national laboratories involved in working on nuclear security and energy often recruit and hire Ph.D.-level chemists in different subareas and then train them to become nuclear and radiochemistry professionals. Expertise can also come from cross-training between different but related technical areas, such as environmental management and nuclear security.

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10

Committee Recommendations

As described in the previous chapters, the committee found that experts in nuclear and radiochemistry comprise a range of disciplinary backgrounds and research interests, who provide capability in academic research and education, nuclear medicine, energy and power, national security, and environmental management. The committee also determined that the needs for nuclear and radiochemistry expertise are barely being met by current supply and that future needs may not be met by the supply projected given current trends. There are two principal reasons for the current and projected challenges in meeting the need for expertise: there is little nuclear and radiochemistry taught at the undergraduate and graduate level and there are too few graduate programs with more than a single nuclear or radiochemist to support education and workforce needs. Adding nuclear and radiochemistry to the core chemistry curriculum and including it in American Chemical Society degree accreditation criteria would be of tremendous benefit for both understanding and redressing the gap between supply and demand for the field.

The committee found that the annual production of Ph.D.s and the number of faculty members in nuclear and radiochemistry appear to have stabilized after the steadily decreasing numbers reported over the past several decades. But the continuation of these trends is not assured. In addition, the capacity to track nuclear and radiochemistry expertise is limited and so it is difficult to accurately assess and predict personnel needs.

The committee commends the current and past efforts of federal agencies to support nuclear and radiochemistry workforce education and development. One excellent example is the long-standing Department of Energy (DOE)-sponsored Summer Schools in Nuclear and Radiochemistry, which have been in place since 1984 and have recently been duplicated by the Department of Homeland Security with a focus in forensics and by ACTINET in Europe, and have helped supplement inadequacies of undergraduate chemistry education. However, the various initiatives have been largely created independently by different federal funding agencies each with a slightly different emphasis on outcome. Thus, there exists a great potential for gaps in funding between the various parts of the academic pipeline, and there is no comprehensive plan to address academic pipeline issues. Furthermore, as with most science funding, it is not clear that currently favorable federal funding levels will continue, despite the critical role of nuclear and radiochemistry in national security and environmental protection. Faculty positions are supported by universities if there is sustained research funding to build and maintain robust programs. Sustained support by one or more of the agencies with basic research and development programs is essential to maintain interest, explore the wealth of exciting and relevant research problems, and provide the major equipment and facilities.

Based on its findings, the committee presents the following recommendations for action that both the public and private sectors can take to ensure an adequate supply of nuclear and radiochemistry expertise in the future.

RECOMMENDATIONS

The committee's recommendations call for action in three main areas of need:

- **Institutional**: structural support and collaboration
- **Educational**: on-the-job training and knowledge transfer and retention
- **Workforce Data**: data collection and tracking of workforce

Institutional Needs

1. **Formalized collaborative partnerships for research and education in nuclear and radiochemistry should be established between universities, national laboratories, and relevant industrial sectors.** Given the relatively small population of nuclear and radiochemists in the United States, it is essential to strengthen the connections between current experts and those who will supply and will need expertise in the future. The committee recommends that the federal agencies that depend on nuclear and radiochemistry expertise—including but not limited to those that funded this study (DHS, DOE, and NSF)—provide the necessary stewardship to ensure its sustainability. Specifically, beyond the individual programs discussed in Chapter 9, the committee recommends the establishment of multiple partnerships[1] between the larger nuclear

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[1] The committee suggests four to six partnerships, roughly based on the specialty (focal) areas in nuclear and radiochemistry (medicine, energy and power, security, environmental

and radiochemistry programs at universities and national laboratories, and the programs of 2- and 4-year colleges, research institutes, medical facilities, and industry. The goals of such partnerships would be to ensure an adequate supply of faculty, staff, students, and postdoctoral fellows to satisfy both current and future professional and academic needs; provide experimental and theoretical facilities; bring the most capable new people into the field; and maintain a position of international leadership in nuclear and radiochemistry.

These partnerships should be a national resource for a well-educated and well-trained workforce in basic and applied nuclear and radiochemical disciplines to meet future demand in all relevant areas of research and application. Coordination among the partnerships will be essential to create a coherent national program to achieve these goals. The partnerships should:

- Maintain international leadership in the most critical areas of basic nuclear and radiochemistry to support the U.S. missions that require this expertise.
- Attract and educate exceptionally capable students to support and advance the knowledge base in nuclear medicine, nuclear power, national security, and environmental stewardship.
- Offer a focused summer school for undergraduates at the junior and senior level.
- Provide support to or collaborate with university chemistry departments that seek expertise in nuclear and radiochemistry, but lack resources to provide additional coursework, operate specialized facilities, or hire new faculty to meet their needs.
- Collaborate in the education of 2- and 4-year college faculty to enable:
    - Preparation of modular educational materials for high schools and colleges that include both class and laboratory work that can be used for distance learning (e.g., webcasts) to compensate for the lack of instructors with sufficient expertise to teach such a course at most institutions.
    - Outreach from undergraduate and top-tier graduate institutions to the K-12 community and to student populations such as those at 2-year colleges through the use of these materials and distance learning.

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management, and basic science) and the number of national laboratories that could provide a foundation of infrastructure and expertise. The national laboratories are geographically widely distributed and have expertise in different areas of nuclear and radiochemistry.

Educational Needs

2. **To meet short-term workforce needs, resources and expertise should be made available to support on-the-job training in national laboratories, industry, and elsewhere.** Educational programs are needed to develop experts in nuclear and radiochemistry for critical and time-sensitive jobs. In many of the relevant employment sectors, required "specialists" or on-the-job training—whether for new B.S. degree holders or midcareer scientists changing fields—cannot be met by the traditional academic system, because of the immediacy of the need or the nature of the work (e.g., classified). Other types of strong educational programs are needed to supply this kind of training. The committee suggests the partnerships described above as a mechanism for effective on-the-job training.
3. **To ensure that long-term critical workforce needs can be met, federal agencies should identify and prioritize urgent requirements for, and fund efforts to ensure, knowledge transfer and retention.** Given the large number of specialized nuclear and radiochemistry experts who are eligible to retire within the next 5 to 10 years, a process is necessary to minimize the impact of losing many years of experience in a short period of time. Federal agencies should develop procedures to formalize the knowledge transfer and retention process, especially at the national laboratories.

Workforce Data Needs

4. **A federal source of supply and demand data for nuclear and radiochemistry expertise should be available.** An appropriate federal agency should establish a program or system to gather and track the metrics necessary to assess supply and demand and to measure any changes resulting from government and academic efforts to improve the sustainability of the human capital pipeline in nuclear and radiochemistry. At a minimum, nuclear chemistry should once again be tracked through the National Science Foundation (NSF) Survey of Earned Doctorates or another federally funded data collection service. The NSF Division of Statistics, Department of Education, National Center for Education Statistics, and Department of Labor, Bureau of Labor Statistics should be called on to assist federal agencies in determining additional suitable metrics for tracking the quantity and quality of nuclear and radiochemistry expertise.

In closing, based on the state of research funding and the academic pipeline, the committee is not very optimistic about the projected state of nuclear and radiochemistry expertise. If trends in funding and academic support continue (including reliance on personnel without expertise in nuclear and radiochemistry and increasing dependence on the use of on-the-job training to cover shortfalls in properly trained personnel), the projected supply of U.S. nuclear and radiochemistry expertise will barely meet basic demands for at least the next 5 years (Table 8-3). The small size of the expertise pool makes it fragile and vulnerable; it should be supported in a more coordinated and strategic manner than it is currently. Furthermore, should there be major funding cuts, policy changes, or world events, the U.S. supply of nuclear and radiochemistry expertise will be inadequate.

A

Study Statement of Task

An ad hoc committee will examine supply and demand for nuclear chemistry expertise in the United States compared with the production of experts with these skills, and discuss possible approaches for ensuring adequate availability of these skills, including necessary science and technology training platforms. It will:

- Estimate the availability and need for experts with nuclear chemistry skills. Include:
    - The current and anticipated availability in 20 years of U.S. experts (both type and number) with nuclear, radio-, and radiation chemistry skills based on current education and training capabilities.
    - The type and number of experts needed in the next 20 years. Include skills necessary to support areas including education, basic science, weapons, non-proliferation, nuclear forensic, medical, and energy sector needs. Estimate the number of these experts who must be U.S. citizens.
- Estimate the gap between availability and need, and discuss the impact of this gap on the relevant sectors.
- Suggest approaches that could be implemented to assure the U.S. supply of experts is adequate for the next 20 years. In particular, discuss models for science and technology training that could provide the necessary cadre of researchers with the appropriate skill set. In doing so the study will:
    - Describe the current availability of U.S. training programs, and assess the capabilities of these programs.
    - Compare current U.S. programs with science and technology training programs in other countries.

  - Provide practical input to current programs and suggest new programs if necessary to meet the anticipated need. In particular, suggest models beyond the traditional apprenticeship model between university professor and graduate student
- Provide others suggestions as applicable for addressing causes of the decline in capability and re-establishing the health and vitality of nuclear, radio-, and radiation chemistry within the United States.

B

Biographical Information

GUEST SPEAKERS

David L. Clark received a B.S. in chemistry in 1982 from the University of Washington, and a Ph.D. in inorganic chemistry in 1986 from Indiana University. His thesis work was recognized by the American Chemical Society with the Nobel Laureate Signature Award for the best chemistry Ph.D. thesis in the United States. Dr. Clark was a postdoctoral fellow at the University of Oxford before joining Los Alamos National Laboratory as a J. Robert Oppenheimer Fellow in 1988. He became a technical staff member in the Isotope and Nuclear Chemistry Division in 1989. Since then he has held various leadership positions at the Laboratory, including program management for nuclear weapons and Office of Science programs, and Director of the Glenn T. Seaborg Institute for Transactinium Science between 1997-2009. Dr. Clark is currently a Fellow of the American Association for the Advancement of Science, a Laboratory Fellow, and Leader of the Plutonium Science Strategy for Los Alamos National Laboratory. His research interests are in the structure and bonding of actinide materials, applications of synchrotron radiation to actinide science, behavior of actinides in the environment, and in the aging effects of nuclear weapons materials. He has published 145 peer-reviewed publications.

Eric Hostetler joined Merck in 2000 from the Washington University St. Louis School of Medicine where he was a postdoctoral associate at the Mallinckrodt Institute of Radiology. He received his B.A. in chemistry from Goshen College and his Ph.D. in organic chemistry from the University of Illinois in Champaign-Urbana. Dr. Hostetler currently manages the radiochemistry group in Merck's Imaging Department. He is responsible for leading the preclinical discovery and clinical translation of novel PET tracers for the quantification of target engagement by therapeutics targeting CNS mechanisms. Data from preclinical and clinical studies with these PET tracers are used to guide the development of therapeutic drug candidates. Dr. Hostetler's research has led to the discovery and application of novel PET tracers for seven different CNS targets.

Samantha E. Kentis is a program manager at the U.S. Department of Homeland Security (DHS) Domestic Nuclear Detection Office's (DNDO's) National Technical Nuclear Forensics Center. She manages the National Nuclear Forensics Expertise Development Program; leads the Center's interagency coordination efforts on national-level nuclear forensics policy and planning among the Departments of Defense, Energy, Homeland Security, Justice, State, and the Intelligence Community; and works closely with the State Department and others as the DNDO lead for nuclear forensics-related international activities. Prior to joining DHS, Ms. Kentis worked in the private sector primarily supporting nuclear forensics R&D efforts at the Defense Threat Reduction Agency. She holds a B.A. in foreign affairs from the University of Virginia and an M.A. in security studies from Georgetown University's Edmund A. Walsh School of Foreign Service.

W. Frank Kinard is the Mebane Professor of Chemistry at the College of Charleston in Charleston, South Carolina. His teaching responsibilities include nuclear chemistry, environmental chemistry, instrumental analysis, and quantitative analysis. He received his B.S. degree in chemistry from Duke University and his Ph.D. in analytical chemistry from the University of South Carolina. He was an Atomic Energy Commission Post-Doctoral Fellow at Florida State University and a research associate in chemical oceanography in the Department of Marine Sciences of the University of Puerto Rico in Mayagüez. His most recent research activities have centered on the application of inductively coupled plasma—mass spectrometry to the analysis of high-level wastes at the Savannah River Site. Currently, he is serving as the director of the "Summer School in Nuclear Chemistry" sponsored by the U.S. Department of Energy and the American Chemical Society at San José State University. He is the secretary of the Division of Nuclear Chemistry and Technology of the American Chemical Society. He has spent his summers for the last two decades as a senior research scientist in the Chemical Technology Division of the Oak Ridge National Laboratory, guest scientist in the Nuclear Chemistry Division of the Lawrence Livermore National Laboratory, and as a visiting scientist at the Savannah River Ecology Laboratory and the Analytical Development Section of the Savannah River Technology Center. He has been a faculty member at the College of Charleston since 1972 and is the author of more than 35 technical publications. Dr. Kinard is an analytical chemist who has worked for the past 20 years in solvent extraction, solution chemistry thermodynamics, and the analysis of high-level radioactive wastes. In the past decade, he has been extensively involved with the Analytical Development Section of the Savannah River Technology Center where he has participated in finding solutions to the many problems related to the analysis of high-level waste tanks and the start-up of the Defense Waste Processing Facility vitrification process. He has participated in review panels for the Characterization, Monitoring and Sensor Technology program for DOE and for the Basic Chemical Sciences panel for the EPA. His main pedagogical interests are in developing experiments involving the use of chemical instrumentation in solving chemical and environmental analytical problems. These experiments emphasize the use of computer based data analyses to answer chemical questions. Recent work has included using the worldwide web as an augmentation to classroom activities. Dr. Kinard received his B.S. from Duke University and his Ph.D. from the University of South Carolina.

Francis Livens is professor of radiochemistry and research director of the Dalton Nuclear Institute in the University of Manchester. He received his Ph.D. in plutonium geochemistry from the University of Glasgow in 1985 and joined the University of Manchester in 1991 where, in 1999, he was the founding director of the Centre for Radiochemistry Research (CRR). He has worked in radionuclide geochemistry, aqueous speciation and spectroscopy, and radioactive waste disposal, with a particular interest in the actinide elements. Dr. Livens provides advice to the U.K. government on nuclear and related matters, and is a member of the Advisory Committee on Radioactive Waste Management.

Tim McCarthy, a two-time graduate of the University of Liverpool, U.K., with a B.Sc. in chemistry, followed by a Ph.D. in organic chemistry in 1989. Dr. McCarthy earned an MBA at Washington University in St. Louis, Missouri, in 2000. He has published more than 45 papers and contributed to four books. He is currently the president of the Academy of Molecular Imaging and founding director and past-president of the Society of Non-Invasive Imagining in Drug Development. In his role at Pfizer Global Research and Development, Dr. McCarthy is responsible for the application of imaging techniques to facilitate the prosecution of compounds in the development portfolio and across all therapeutic areas. Additionally, his role is focused on the application of innovative imaging technologies to accelerate drug development. Since 2003, Dr. McCarthy has held senior management roles with Pfizer Global R&D. Prior to joining the company, he held a number of academic and industry positions in the field of positron emission tomography, including more than 10 years at Washington University, St. Louis, Missouri, in the departments of Radiology and Biomedical Engineering and two years at Pharmacia Corporation where he was group manager of tracer technologies and clinical technologies in experimental medicine.

Jason Pruet is a program manager in the Office of Stockpile Stewardship at the National Nuclear Security Administration (NNSA). His current focus is on developing the science basis supporting maintenance of the U.S. stockpile into an indefinite future without nuclear testing. Prior to joining NNSA Mr. Pruet was at Lawrence Livermore Laboratory. His efforts at Livermore centered on basic research in nuclear physics and astrophysics, applied weapons research, and development of new technologies for detecting clandestine nuclear weapons.

Larry Rahn is currently the program manager in the DOE/SC Office of Basic Energy Sciences (BES), in the area of Separations and Analysis. He also works in the Heavy Element Chemistry program. Before joining BES in January 2011, Dr. Rahn was a senior scientist in the Transportation Energy Center at Sandia National Laboratories, Livermore, California, and worked on assignment at BES since 2006.

After earning his Ph.D. in physics at Kansas State University and performing postdoctoral studies at Michigan State University, Dr. Rahn joined Sandia where he worked for 35 years and contributed to early efforts that led to the founding of the Combustion Research Facility (CRF). He became a principal investigator in the BES Chemical Science Program at the CRF, earning a promotion to distinguished member of technical staff and election to Fellow of the Optical Society of America. After 17 years of research in laser-based combustion diagnostics, he managed the Reacting Flow Research Department at the CRF for almost a decade, when he was promoted to senior scientist.

Dr. Rahn's research has resulted in more than 60 journal publications in Raman and nonlinear optical spectroscopy, combustion diagnostics, molecular physics, solid state physics, and collaborative data sharing environments.

Michael J. Scott is an associate professor in the Chemistry Department at the University of Florida, currently serving as program director of solid state and materials chemistry in the Division of Materials Research, and program director of macromolecular, supramolecular and nanochemistry in the Division of Chemistry at the National Science Foundation. His research interests are in development of efficient recognition agents for selective actinide extractions and the design of reactive transition metal catalysts. Dr. Scott earned a Ph.D. in inorganic chemistry in 1994 from Harvard University and a B.S. in chemistry 1988 from the University of California, Berkeley. He held an NIH Postdoctoral Fellow from 1994-1997 at the Massachusetts Institute of Technology, and joined the faculty of the University of Florida in 1997. Dr. Scott's honors include: a National Institutes of Health-Postdoctoral Fellowship, Research Corporation-Research Innovation Award, National Science Foundation-CAREER Award, Alfred P. Sloan Foundation Research Fellowship, and he is a Fellow of the Royal Society of Chemistry. Dr. Scott also serves as co-director-research experiences for undergraduate program at the University of Florida.

COMMITTEE MEMBERS

Chair

C. Bradley Moore (NAS) is a professor emeritus in the University of California, Berkeley, Department of Chemistry. Dr. Moore had direct management responsibility for Berkeley's nuclear chemistry program, as chemistry department chair, as dean, and as director of the Chemistry Division (including chemistry of the actinides) at Lawrence Berkeley National Laboratory (LBNL). From 1988 to 2000, he served on advisory committees at Los Alamos that reviewed nuclear chemistry programs. Dr. Moore has also served as vice president for research at Ohio State and Northwestern Universities during most of this past decade. He was also a member of the governing board of both Argonne and Fermi National Labs and was instrumental in creating the current arrangement for a shared management of those labs that includes Northwestern University, the University of Chicago, the University of Illinois, and others. Dr. Moore was elected to the National Academy of Sciences in 1986.

Members

Carolyn J. Anderson is a professor of radiology, and pharmacology and chemical biology, and is the director of the Molecular Imaging Laboratory at the University of Pittsburgh. Dr. Anderson received her B.S. in chemistry in 1985 from the University of Wisconsin-Superior, and her Ph.D. in inorganic chemistry in 1990 from Florida State University, where she carried out her dissertation research with Professor Gregory R. Choppin in the area of actinide chemistry. After obtaining her Ph.D., Anderson was a research associate in the Mallinckrodt Institute of Radiology at Washington University

School of Medicine in St. Louis, Missouri, in Professor Michael J. Welch's group. In 1993, she was promoted to assistant professor of radiology, and held the position of professor in the Departments of Radiology, Biochemistry & Molecular Biophysics, and Chemistry from 2007-2011, before moving to the University of Pittsburgh in May 2011. Dr. Anderson's research interests include the development and evaluation of novel radiometal-based radiopharmaceuticals for diagnostic imaging and targeted radiotherapy of cancer and other diseases. She pioneered the development of copper-64-based radiopharmaceuticals, and her research group carries out research on the interface of chemistry and biology. She has had NIH funding since 1994 and has co-authored over 135 peer-reviewed and invited publications, mostly in the area of developing radiopharmaceuticals for oncological imaging and targeted radiotherapy. Dr. Anderson has been actively involved in the education and training of graduate and undergraduate students in the areas of nuclear and radiochemistry, imaging sciences, and nanotechnology.

Trish Baisden is the deputy director of the National Ignition Campaign (NIC), a national, multi-laboratory effort led by the National Ignition Facility (NIF) and Photon Science Directorate at the Lawrence Livermore National Laboratory (LLNL). NIC is the scientific and technology development program on NIF focused on using inertial confinement fusion to achieve ignition and thermonuclear burn in the laboratory. Dr. Baisden is a nuclear chemist and during her 30-year career at LLNL she has held a number of technical management positions including division leader for analytical sciences, deputy director of the Seaborg Institute, materials program leader for NIF, chief scientist and deputy associate director for the Chemistry and Material Sciences Directorate. Professionally she has served on numerous study panels and review committees, as an editor of the journal Radiochimica Acta, and chairperson of the American Chemical Society's Division of Nuclear Chemistry and Technology. Dr. Baisden's research interests include nuclear fusion, lasers and optical materials, heavy ion reactions, heavy element fission properties, the chemistry of 4 and 5f elements, and nuclear power and advanced fuel cycles. Dr. Baisden earned a B.S. in 1971 and a Ph.D. in 1975 in chemistry from Florida State University and then held a 2-year postdoctoral appointment with Professor Glenn T. Seaborg at the University of California, Lawrence Berkeley National Laboratory, before joining the staff at LLNL.

Carol Burns is a Laboratory Fellow at Los Alamos National Laboratory, and serves as the group leader for nuclear and radiochemistry in the Chemistry Division. She received her Ph.D. in chemistry from the University of California, Berkeley in 1987. She came to LANL as a J. Robert Oppenheimer Postdoctoral Fellow, and has been employed at LANL since that time, serving in a variety of line and program management positions. She served as a senior policy advisor in the White House Office of Science and Technology Policy in 2003-2004. She provided technical and policy assistance on national and homeland security science and technology issues involving defense infrastructure (including workforce issues) and threat preparedness, as well as coordination of science and technology policies within the national security and intelligence communities. She continues to support LANL in the coordination of activities in nuclear forensics, including working with the interagency on workforce pipeline and educational program development. She established the first summer undergraduate school in nuclear forensics, funded by the Department of Homeland Security. She was awarded the LANL Fellows Publication Prize in 2002, and was named a Laboratory Fellow in 2003. She was named a Fellow of the American Association for the Advancement of Science in 2009. She is a recognized expert in actinide and radionuclide chemistry, with more than 95 peer-reviewed publications and invited book chapters, and has served on a number of editorial boards, review boards, and advisory panels.

Ronald Chrzanowski is a senior power plant manager with Exelon Nuclear. He has 30 years experience in nuclear power plants including chemistry, engineering, nuclear oversight, operations, regulatory assurance, licensing, and security. He is currently the Exelon Chemistry Corporate functional area manager, where he is responsible for supervising 4 experienced corporate chemists, leading the chemistry peer group, and chemistry governance and oversight functional area for 17 nuclear units at 10 stations. Mr. Chrzanowski previously held the position of chemistry manager at Exelon's LaSalle Station, where for 5 years he was responsible for managing the chemistry department of 26 employees including 13 represented employees and budget responsibility for $10M/yr. His prior experience includes obtaining a senior reactor operator's license at the Byron Nuclear Generating Station as well as manager positions in many other departments over the years. Mr. Chrzanowski received a B.S. in electrical engineering from Marquette University. His industry leadership service includes EPRI Chemistry, RP, LLW TAC (Technical Advisory Committee) member for 2.5 years, Regulatory Ground Water Protection Program Working Group 2008-2009, and Radiation Sourcebook Committee 2010. Previously he was the EPRI ORSERG (Operational Reactor Safety Engineering Review Group) chairman, 2001-2002, and currently he is the EPRI Chemistry, LLW, RP TAC vice chairman.

Sue B. Clark is an expert in environmental chemistry of plutonium and other actinides, chemistry of high-level radioactive waste systems, and chemistry of actinide-bearing solid phases in natural environments. She is Regents Professor of Chemistry at Washington State University in Pullman. She has previously served as the interim dean of the College of Sciences at WSU (statewide), and the interim vice chancellor for academic affairs at Washington State University, Tri-Cities campus. Previously, she was an assistant research ecologist at the University of Georgia's Savannah River Ecology Laboratory and senior scientist at Westinghouse Savannah River Company's Savannah River Technology Center. She currently is a member of the U.S. Department of Energy's Basic Energy Sciences Advisory Committee. She has received several awards, including the Westinghouse Distinguished Professor of Chemistry (2000 to present), the Edward R. Meyer Distinguished Professor of Chemistry (1998 to 2000), and the Young Faculty Achievement Award (1998 to 1999) in the College of Sciences at Washington State University. She is a member of the American Chemical Society, the American Association for the Advancement of Science, and Sigma Xi, the Scientific Research Society. Dr. Clark received her Ph.D. in inorganic and radiochemistry from Florida State University. She has previously served on the Nuclear and Radiation Studies Board and several National Research Council committees.

Richard B. Freeman holds the Herbert Ascherman Chair in Economics at Harvard University. He is currently serving as faculty co-director of the Labor and Worklife Program at the Harvard Law School. He directs the National Bureau of Economic Research-Sloan Science Engineering Workforce Projects, and is senior research fellow in labor markets at the London School of Economics' Centre for Economic Performance. Dr. Freeman is a fellow of the American Academy of Arts and Sciences and is currently serving as a member of the AAAS Initiative for Science and Technology. Dr. Freeman served on the study on Policy Implications of International Graduate Students and Postdoctoral Scholars in the United States. He also served on five panels of the National Research Council, including the Committee on National Needs for Biomedical and Behavioral Scientists. He received the Mincer Lifetime Achievement Prize from the Society of Labor Economics in 2006. In 2007 he was awarded the IZA Prize in Labor Economics. His recent publications include: Can Labor Standards Improve Under Globalization (2004), Emerging Labor Market Institutions for the 21st Century (2005), America Works: The Exceptional Labor Market (2007), What Workers Want (2007 2nd edition), What Workers Say: Employee Voice in the Anglo American World (2007), International Differences in the Business Practices & Productivity of

Firms (2009), Science and Engineering Careers in the United States (2009), Reforming the Welfare State: Recovery and Beyond in Sweden (2010), and Shared Capitalism at Work: Employee Ownership, Profit and Gain Sharing, and Broad-based Stock Options (2010). His forthcoming IZA Prize book is Making Europe Work: IZA Labor Economics Series (2010). Dr. Freeman has also received an NSF Science of Science and Innovation Policy Award # 0915670 "DAT: Scientists and Engineers as Agents of Technological Progress: Measuring the Returns to R&D and the Economic Impact of Science & Engineering Workers."

Howard Hall is the University of Tennessee and Oak Ridge National Laboratory Governor's Chair in Nuclear Security, in the department of nuclear engineering at UT. He also serves as director of the Howard H. Baker Jr. Center for Public Policy's Global Security Policy Program. Dr. Hall received his Ph.D. in chemistry (focused on nuclear and radiochemistry) from the University of California in 1989, and his B.S. in chemistry from the College of Charleston in 1985. Prior to joining UT, he spent 20 years at Lawrence Livermore National Laboratory in Northern California, where he led major scientific and operational missions in nuclear and homeland security. Dr. Hall is a member of the ANS, the APS, the ACS, and is a Fellow of the American Institute of Chemists. His research interests include nuclear security applications, including proliferation detection, counter-proliferation, detection of and response to radiological or nuclear threats, radiochemistry, nuclear forensics, and applications of nuclear-based methods to other security needs (such as explosives detection). His work with the Baker Center focuses on the intersection of science, security, and public policy.

Lester R. Morss began his scientific career in inorganic chemistry and radiochemistry by carrying out research on the actinide elements uranium through californium under Professor Burris B. Cunningham, achieving a Ph.D. at University of California, Berkeley in 1969. After postdoctoral study with James W. Cobble at Purdue University, he reached the rank of full professor of chemistry at Rutgers University, New Brunswick, New Jersey, doing research in synthetic inorganic chemistry and thermochemistry of transition elements. He joined the Chemistry Division of Argonne National Laboratory in 1980, where he resumed his primary research focus of solid-state and thermochemistry of the transuranium elements. After reaching the rank of senior chemist at Argonne, he was elected a fellow of American Association for the Advancement of Science and spent 6 months as an Alexander von Humboldt senior research scientist at the University of Hannover, Germany, in 1992. He retired from Argonne in 2002 and then served until 2010 as program manager for heavy element chemistry in the Office of Basic Energy Sciences of U.S. Department of Energy. He resides in Columbia, Maryland, where he is now an adjunct professor of chemistry at University of Maryland, College Park.

Graham F. Peaslee is a professor and chair of the chemistry department at Hope College, where he has been doing research and teaching for the past 18 years. He is a member of the Division of Nuclear Chemistry and Technology of the ACS and the Division of Nuclear Physics of the APS. He chairs the Coryell Award Committee for undergraduate research for the DNCT, and is currently a councilor for the Chemistry Division of the Council on Undergraduate Research, and is past-chair of the Leadership Group for Research Experiences for Undergraduates for the Chemistry Division of the National Science Foundation. He has served on an IAEA panel for "Enhancing Nuclear Science Education and Training using Accelerators" and runs the Hope College Ion Beam Analysis Laboratory. He has been funded by the NSF for 18 years as co-PI of the Hope College Nuclear Group, and is currently funded to study radioactive nuclear beam reactions, as well as pursuing interdisciplinary nuclear science that includes Particle Induced X-ray Emission, Rutherford Backscattering and Ion-Beam-Induced Luminescence studies. This cross-disciplinary research has expanded to include environmental and forensic applications, including a nuclear forensics project funded by the Department of Homeland Security. Dr. Peaslee has more than 145 refereed publications, which include more than 100 undergraduate co-authors.

Georgine M. Pion is a research associate professor in the Quantitative Methods Program within the department of psychology and human development at Vanderbilt University. Dr. Pion's research has focused on career development and research policy, particularly as it pertains to determining the effectiveness of training programs of scientists in the biomedical, behavioral, and clinical sciences. She conducted a large-scale evaluation of predoctoral research training programs in the biomedical and behavioral sciences for the National Institutes of Health (NIH) as well as evaluations of peer review in the neurosciences, clinical, and behavioral sciences for the NIH's Center of Scientific Review. Additionally, her work has involved evaluations of other research training initiatives, including the Burroughs Wellcome Career Award in the Biomedical Sciences and the American Association of Gynecology and Obstetrics Foundation Scholars program. She has served as chair of the Technical Advisory Committee for the Survey of Earned Doctorates and as a member of several NRC and IOM committees involved in research and clinical training, including the Panel on the Career Outcomes of Men and Women Scientists and Engineers, Evaluation of the

Lucille S. Markey Charitable Foundation, the Committee on Bridges to Independence, the Committee on Biomedical and Behavioral Personnel, and the Committee on Training Needs of Health Professionals in Domestic Violence. Dr. Pion received a Merit Award from the NIH in 1999 for her survey and evaluation work and is an associate member of the National Academy of Sciences. Dr. Pion obtained her Ph.D. from Claremont University in 1980 and completed a National Research Service Award (NRSA) postdoctoral traineeship in Northwestern University's Evaluation and Research Methodology program.

Henry F. VanBrocklin is currently professor of radiology and biomedical imaging at the University of California San Francisco (UCSF) and director of radiopharmaceutical research in the Center for Functional and Molecular Imaging. His work in the field spans many disciplines from short-lived radioisotope production to the creation of fluorine-18 and carbon-11 labeling chemistry strategies for new radiotracer preparation and application. His current research interests include development of automated devices for the production of fluorine-18 labeled molecules, preparation of radiopharmaceutical probes for PET and SPECT blood flow measurement, design of imaging agents targeting cancer cell surface markers, and the application of imaging in drug development. He has on-going collaborations with several pharmaceutical companies. He has been very active within the SNM (Society of Nuclear Medicine) leadership as the president of the Radiopharmaceutical Sciences Council and recently as president of the Molecular Imaging Center of Excellence. He participated in the development and implementation of the SNM's Molecular Imaging strategic five-year plan. He has been an advocate for the appropriate regulation of radiopharmaceuticals working on multiple task forces within the SNM and in workshops with the FDA. He led a task force to respond to the FDA regarding the exploratory IND (XIND) draft guidance and has subsequently successfully implemented XIND studies at UCSF using the final FDA guidance. Additionally, Dr. VanBrocklin has overseen the complete build out of a state-of-the-art radiochemistry, imaging, training and treatment facility at UCSF for basic R&D and preclinical studies as well as clinical applications.

John F. Wacker is a laboratory fellow at the Pacific Northwest National Laboratory (PNNL) in Richland, Washington. Dr. Wacker currently works on nuclear forensic analysis and related fields, as well as working on projects that improve and utilize various ultratrace analytical techniques. He supports both the U.S. and international Technical Nuclear Forensics communities as a lead technical expert on the laboratory analysis of nuclear and radiological materials and on nuclear materials production and usage. From May 2007 to May 2010, Dr. Wacker was detailed to the U.S. Department of Energy (DOE) in Washington, DC, where he served as the chief scientist on the Nuclear Materials Information Program. In his role he advised the DOE and other U.S. government agencies and departments on issues relating to nuclear materials and nuclear forensics. Since returning to PNNL in May 2010, he has continued advising the DOE on issues that include nuclear material analysis, sample archives, and data libraries, as well as assisting at the interagency level in the development of policy-level requirements for nuclear forensics. Prior to May 2007, Dr. Wacker managed research and development programs at PNNL that developed and applied nuclear detection and analysis techniques for the DOE and other U.S. government departments and agencies. From 1993 to 2004, Dr. Wacker managed an analytical laboratory at PNNL that performs nuclear material analyses in support of environmental analysis, treaty verification, and other nuclear safeguards activities. Dr. Wacker earned a Ph.D. in planetary sciences from the University of Arizona and a S.B. in physics from the Massachusetts Institute of Technology.

C

Public Meeting Schedule and Guest Speakers

MEETING 2, MARCH 16, 2011

Location: Keck Building, Room 204

10:00-10:15 a.m.
Welcome and Introductions, Bradley Moore, chair

10:15 a.m.-12:15 p.m
Discussion of Statement of Task with Study Sponsors
Larry Rahn, Basic Energy Sciences, Department of Energy (DOE)
Dennis Phillips, Nuclear Physics, DOE
Jim Bresee, Nuclear Energy, DOE
Jason Pruet, National Nuclear Security Administration, DOE
Samantha Kentis, Domestic Nuclear Detection Office, Department of Homeland Security

12:15-1:15 p.m.
Lunch (cafeteria)

1:15-2:15 p.m.
Radiochemistry and Nuclear Medicine Needs
Eric Hostetler, Merck
Tim McCarthy, Pfizer

2:15-3:15 p.m.
Weapons, Security, and Stockpile Stewardship Needs
David Clark, Los Alamos National Laboratory (via phone)

MEETING 3, MAY 9, 2011

Keck Center, Room 101
500 Fifth Street, NW
Washington, DC 20001

10:00 a.m.
Welcome and Introductions, Brad Moore, chair

10:15 a.m.
A Perspective from the United Kingdom
Francis Livens, University of Manchester (teleconference)

11:15 a.m.
Statement of Task Discussion with Study Sponsor
Michael Scott, Chemistry Division, National Science Foundation
Frank Wong, Department of Homeland Security

12:15-1:15 p.m.
Lunch

1:15-2:15 p.m.
Summer Schools in Nuclear Chemistry, Frank Kinard

D

Questionnaire Descriptions

D1. Chairs of U.S. Chemistry Departments

D2. Members of Society Of Radiopharmaceutical Sciences and the Radiopharmaceutical Sciences Council of the Society of Nuclear Medicine

D3. Chemistry Managers and Vendors of Commercial Nuclear Power Plants

D1. CHAIRS OF U.S. CHEMISTRY DEPARTMENTS

The questionnaire below was sent via e-mail to 144 department chairs and 44 schools responded (a 30 percent response rate). Respondents were given the options of replying to questionnaire on a web-based interface, FAX, or postal mail. Department chairs (see Appendix H) were identified from the 2009 ACS Directory of Graduate Research (ACS 2009) and top 100 NRC chemistry departments (NRC 2011).

Questionnaire

A. Does your department offer courses which are devoted to or in part to nuclear and/or radiation chemistry? Yes or no (Circle one.)
   1. Course title:__________________________
   2. Level: (Circle one.) lower division, upper division, graduate
   3. Typical enrollment_______
   4. Lab work included? Yes or no
   5. If broader course, about what percent devoted to nuclear/radiochemistry?

B. Is nuclear/radiochemistry material included in general lecture or lab courses?
   1. Course title:__________________________
   2. Approximately what fraction of the course lecture or lab time is devoted to nuclear/radiochemistry? ______

C. Does your department faculty include nuclear and/or radiochemists? If so, please provide their names and areas of interests specified according to the following designations:
   1. Fundamental Nuclear chemistry—interest in nuclear properties (structures, reaction, fission, etc.).
   2. Chemistry of radioactive elements—actinide and lanthanide chemistry, other elements such as Tc, Ra, Po, etc.
   3. Analytical applications—uses activation analysis, tracers, etc. to measure elemental concentrations in geochemical, environmental, biological applications.
   4. Nuclear probes for chemical studies—e.g., Mössbauer effect, nuclear orientation experiments, perturbed angular correlations.
   5. User of tracer techniques and labeled compounds.
   6. Nuclear medicine and radiopharmaceutical chemistry.

Faculty Name	Primary Field (Circle one.)	Second Area (Circle one.)	Directs Grant Research (Circle one.)
________________	1 2 3 4 5 6	1 2 3 4 5 6	Yes No
________________	1 2 3 4 5 6	1 2 3 4 5 6	Yes No
________________	1 2 3 4 5 6	1 2 3 4 5 6	Yes No
________________	1 2 3 4 5 6	1 2 3 4 5 6	Yes No
________________	1 2 3 4 5 6	1 2 3 4 5 6	Yes No
________________	1 2 3 4 5 6	1 2 3 4 5 6	Yes No
________________	1 2 3 4 5 6	1 2 3 4 5 6	Yes No
________________	1 2 3 4 5 6	1 2 3 4 5 6	Yes No
________________	1 2 3 4 5 6	1 2 3 4 5 6	Yes No

The number of faculty in these areas in 2001 was _______.
The number of graduate students in research in these areas presently?____
In 2001?_______

D2. MEMBERS OF SOCIETY OF RADIOPHARMACEUTICAL SCIENCES AND THE RADIOPHARMACEUTICAL SCIENCES COUNCIL OF THE SOCIETY OF NUCLEAR MEDICINE

The questionnaire below was sent via e-mail from the Society of Nuclear Medicine (SNM) to its 760 members of the Society of Radiopharmaceutical Sciences (SRS) and the Radiopharmaceutical Sciences Council (RPSC). Respondents anonymously completed the questionnaire via a web-based interface.

Questionnaire

The National Academy of Sciences Committee on Assuring a Future U.S.-based Nuclear Chemistry Expertise in Nuclear/Radiochemistry has been charged with examining supply and demand for nuclear, radio-, and radiation chemistry expertise in the United States. To make recommendations for ensuring adequate availability of these skills, including necessary science and technology training, the committee is seeking information about workforce needs in the nuclear medicine field. Your input, as a member of the Society of Radiopharmaceutical Scientists and Radiopharmaceutical Sciences Council of the Society of Nuclear Medicine, is critical. The data gathered will help provide practical input to current educational programs and suggest ways to ensure the health and vitality of nuclear, radio-, and radiation chemistry in the United States.

If you have any questions, please email Sheena Siddiqui at ssiddiqui@nas.edu.

1. Do you consider yourself a nuclear and/or radiochemist, or do you work with radiotracers as part of your job? (If no, then survey is complete. Required)
    - Yes
    - No (Skip to end of survey and click Submit.)

2. What is your highest degree?
    - Bachelors
    - Masters
    - Ph.D.
    - M.D.
    - M.D., Ph.D.
    - Pharm.D.
    - Other (Please specify.)

3. What is the primary discipline of your degree (Please be as specific as possible (e.g. biological, chemistry, nuclear physics, etc.))?

4. In what country do you work? (Required.)

5. In what year were you born?

6. Which of the following best describes your primary employer?
   - College or university
   - University-affiliated research institute
   - Free-standing research institute or organization
   - Federal government agency
   - State or local government agency
   - Hospital or clinic
   - For-profit business or company
   - Self-employed
   - Other non-profit organization not mentioned above (e.g., professional association)
   - Other (Please specify.)

7. Do you currently have a faculty appointment? (If no, skip to question 10.)
   - Yes
   - No

8. In what department is your faculty appointment? (Please identify the departments of any joint appointments or secondary appointments you have.)
   - Faculty appointment
   - Joint appointment
   - Secondary appointment

9. What is your academic rank? (Select one and skip to question 11.)
   - Assistant professor
   - Associate professor
   - Full professor
   - Research assistant professor
   - Research associate professor
   - Research professor
   - Clinical assistant professor
   - Clinical associate professor
   - Clinical professor
   - Other (Please specify.)

10. What is the title of your primary employment position?

11. In the past 10 years, have you been involved in training undergraduate students, graduate students, medical students, and/or postdoctoral fellows in a research laboratory setting? (If no, skip to question 14.)
    - Yes
    - No

12. For each of the following, indicate approximately how many individuals you have trained in the laboratory. (Enter "0" if you haven't trained anyone. Do NOT count students whom you are currently training.)
    - Undergraduate students
    - Master's students
    - Doctoral students
    - Medical students
    - Postdoctoral fellows and trainees
    - Other (Please describe.)

13. Currently, how many of the following types of students are you training in your lab?
    - Undergraduate students
    - Master's students
    - Doctoral students
    - Medical students

14. Based on your experience and knowledge of the workforce, how would you rate the adequacy of the nuclear/radiochemistry workforce over the next 5 years?
    - The supply of nuclear/radiochemists is substantially larger than the demand for these individuals.
    - The supply of nuclear/radiochemists is somewhat larger than the demand for these individuals.
    - The supply of nuclear/radiochemists is slightly larger than the demand for these individuals.
    - The supply of nuclear/radiochemists is about the same as the demand for these individuals.
    - The supply of nuclear/radiochemists is slightly smaller than the demand for these individuals.
    - The supply of nuclear/radiochemists is somewhat smaller than the demand for these individuals.
    - The supply of nuclear/radiochemists is substantially smaller than the demand for these individuals.

D3. CHEMISTRY MANAGERS AND VENDORS OF COMMERCIAL NUCLEAR POWER PLANTS

The questionnaire below was sent via e-mail from committee member Ronald Chrzanowski to chemistry managers of all 65 nuclear power plants in the United States (listed in Appendix I). Responses are presented in an aggregated format.

The purpose of survey is to find out as much as possible about the supply and demand of nuclear chemists and radiochemists. Indications are that there appears to have been a sharp increase in the demand for graduates with nuclear chemistry degrees and there also appears to be a greater demand than there is a supply. These questions, along with a complementary survey sent to universities, are designed to determine if this supply-demand gap is real and if so, how it is likely to evolve in the coming years.

Plant or Organization Name: ____

1. Does your organization employ Chemists holding a BS, MS or Ph.D. in Nuclear Chemistry or Radiochemistry?
2. Roughly how many Nuclear Chemistry or Radiochemistry degree holders does it employ?
3. How many degreed Chemists do you employ in total?

For the following questions, base your answers on the following description of a Nuclear Chemist or Radiochemist: a Chemist that deals with radiochemistry or reactor chemistry.

4. How many openings did you have for nuclear or radiochemists in the past year?
5. How many of these openings did you fill with nuclear or radiochemistry graduates?

6. Do you anticipate hiring nuclear or radiochemists in the next 20 years? If so, how many do you anticipate hiring? Please provide an estimate by degree.

Total number of hires in next:	5 yrs	5-10 yrs	10-15 yrs	15-20 yrs
Nuclear or Radiochemisty BS	__________	__________	__________	__________
Nuclear or Radiochemistry MS	__________	__________	__________	__________
Nuclear of Radiochemistry PhD	__________	__________	__________	__________

7. Have the type of tasks assigned to nuclear or radiochemistss today changed from that over the past several years?
8. What are the major tasks for nuclear or radiochemists today?
9. Have you had difficulty finding nuclear or radiochemists to fill your positions?
10. Do you hire nuclear or radiochemists out of school or do you require a minimum number of years in the discipline?
11. Do you hire non-nuclear or non-radiochemists and train them in-house to perform the nuclear or radiochemist functions?

REFERENCES

ACS (American Chemical Society). 2009. DGRweb 2009 [online]. Available: http://dgr.rints.com/ [accessed September 7, 2011].

NRC (National Research Council). 2011. *Data-Based Assessment of Research-Doctorate Programs in the United States*. J. P. Ostriker, C. V. Kuh, and J. A. Voytuk, Eds; Washington, DC: The National Academies Press. Available online at www.nap.edu/rdp/. Also see: http://graduate-school.Ph.D.s.org/rankings/chemistry/rank/larger.

E

2008 Nuclear and Radiochemistry Faculty List

TABLE E-1 2008 List of U.S. Nuclear and Radiochemistry Ph.D. and M.S. Advisors Identified by the American Chemical Society Division of Nuclear Chemistry and Technology (includes non-U.S. faculty)

Advisor	Department	U.S./Canadian School	Thesis Year	Thesis Subject Term(s)*
Albrecht-Schmitt, Thomas	Department of Chemistry	Auburn University	1997	Chemistry
Anderson, Carolyn	School of Medicine	Washington University, St. Louis	1990	Chemistry, Nuclear chemistry, Analytical chemistry
Benny, Paul Douglas	Department of Chemistry	Washington State University	2001	Nuclear chemistry
Bickley, Abigail	Department of Chemistry	Michigan State University	2004	Nuclear chemistry, Particle physics
Blatchley, Charles	Department of Physics	Pittsburg State University	1984	Nuclear physics
Cerny, Joseph	Department of Chemistry	University of California, Berkeley	1962	Nuclear physics
Clark, Aurora	Department of Chemistry	Washington State University	2003	Chemistry
Clark, Sue Brannon	Department of Chemistry - Analytical	Washington State University	1989	Chemistry, Environmental science
Czerwinski, Kenneth	Department of Chemistry - Radiochemistry	University of Nevada, Las Vegas	1992	Nuclear chemistry
de Souza, Romualdo	Department of Chemistry	Indiana University	1987	Nuclear chemistry
DeVol, Timothy	Department of Environmental Engineering and Earth Sciences	Clemson University	1993	Organic chemistry, Nuclear physics
Dixon, David	Department of Chemistry	University of Alabama	1976	Chemistry
Ensor, Dale Duvall	Department of Chemistry	Tennessee Technological University	1977	Chemistry
Fjeld, Robert	Department of Environmental Engineering and Earth Sciences	Clemson University	1976	Nuclear physics, Energy
Folden, III, Charles	Cyclotron Institute	Texas A&M University	2004	Nuclear chemistry, Nuclear physics
Gorden, Anne Elizabeth	Department of Chemistry and Biochemistry	Auburn University	2002	Chemistry, Organic chemistry
Hoffman, Darleane	Department of Chemistry	University of California, Berkeley	1951	Nuclear chemistry
Hoffman, Timothy	Department of Chemistry	University of Missouri, Columbia	1996	Radiation, Pharmacology, Radiology
Jia, Jiangyong	Department of Chemistry	State University of New York at Stony Brook	2003	Nuclear physics, Particle physics
Jurisson, Silvia	Department of Chemistry	University of Missouri, Columbia	1982	Chemistry
Karol, Paul Jason	Department of Chemistry	Carnegie Mellon University	1967	Nuclear chemistry
Krohn, Ken	Department of Chemistry, Department of Radiology	University of Washington	1971	Nuclear chemistry
Lacey, Roy	Department of Chemistry	State University of New York at Stony Brook	1987	Nuclear chemistry

Lisic, Edward	Department of Chemistry	Tennessee Technological University	1986	Chemistry
Loveland, Walter David	Department of Chemistry	Oregon State University	1966	Nuclear physics, Energy
Mantica, Paul Francis	Department of Chemistry	Michigan State University	1990	Nuclear chemistry, Nuclear physics
Mignerey, Alice Cox	Department of Chemistry and Biochemistry	University of Maryland at College Park	1975	Nuclear chemistry
Moretto, Luciano	Department of Chemistry	University of California, Berkeley	—	—
Morrissey, David Joseph	Department of Chemistry	Michigan State University	1978	Nuclear chemistry
Nash, Kenneth	Department of Chemistry - Analytical	Washington State University	1979	Chemistry
Natowitz, Joseph Bernard	Department of Chemistry	Texas A&M University	1965	Nuclear physics
Nitsche, Heino	Department of Chemistry	University of California, Berkeley	1980	Nuclear chemistry, Physical chemistry
Paulenova, Alena	Department of Chemistry	Oregon State University	1985	Nuclear chemistry
Paviet-Hartmann, Patricia	Department of Chemistry - Radiochemistry	University of Nevada, Las Vegas	1992	Nuclear chemistry
Powell, Brian A.	Department of Environmental Engineering and Earth Sciences	Clemson University	2004	Radiation, Geochemistry, Environmental science
Rengan, Krishnaswamy	Department of Chemistry	Eastern Michigan University	1966	Nuclear chemistry
Robertson, John David	Department of Chemistry	University of Missouri, Columbia	1986	Nuclear chemistry
Sarantites, Demetrios George	Department of Chemistry	Washington University, St. Louis	1963	Nuclear chemistry
Schröder, Wolf-Udo	Department of Chemistry	University of Rochester	1971	Nuclear chemistry
Sobotka, Lee Gordon	Department of Chemistry	Washington University, St. Louis	1982	Nuclear chemistry
Sudowe, Ralf	Department of Chemistry - Radiochemistry, Department of Health Physics and Chemistry (M.S.)	University of Nevada, Las Vegas	1999	Nuclear chemistry
Tubbs, Laura Ellen	Department of Chemistry	Rochester Institute of Technology	1983	Nuclear chemistry
Wai, Chien	Department of Chemistry	University of Idaho	1967	Chemistry
Wall, Nathalie	Department of Chemistry - Analytical	Washington State University	1993	Nuclear chemistry
Welch, Michael	School of Medicine, Department of Chemistry	Washington University, St. Louis	1965	Nuclear chemistry
Yates, Steven Winfield	Department of Chemistry	University of Kentucky	1973	Nuclear chemistry, Nuclear physics
Yennello, Sherry	Department of Chemistry	Texas A&M University	1990	Nuclear chemistry, Nuclear physics
Yoo, Choong-Shik	Department of Chemistry	Washington State University	1986	Chemistry
Zoller, William Harper	Department of Chemistry	University of Washington	1970	Nuclear chemistry

*According to ProQuest Dissertations and Theses (PQDT) database.

SOURCE: ACS 2008, 2009; ProQuest 2011.

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ACS (American Chemical Society). 2008. Universities Offering M.S. and Ph.D. Programs in Nuclear and Radiochemistry. American Chemical Society, Division of Nuclear Chemistry and Technology [online]. Available: http://spinner.cofc.edu/~nuclear/ACS%20NUCL%20and%20RADIOCHEM%20EDU%20US%20and%20CAN%20List11-12-08.pdf [accessed September 7, 2011].

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F

Data Collection from National Laboratories

The following individuals at contractor-operated national laboratories provided the committee with information on the dates indicated about numbers of their employees with nuclear and radiochemistry related skills: Emilio Bunel, Argonne National Laboratory (July 28, 2011); Leonard Mausner, Brookhaven National Laboratory (May 9, 2012); Carol Burns, Los Alamos National Laboratory (May 9, 2011); Cynthia Coolahan, Bradley Moore, and Steve Leone, Lawrence Berkeley National Laboratory (August 26, 2011); Trish Baisden, Lawrence Livermore National Laboratory (May 17, 2011); Patricia Paviet-Hartmann, Idaho National Laboratory (June 27, 2011), Michelle Buchanan, Oak Ridge National Laboratory (December 6 and 8, 2011); John Wacker; Pacific Northwest National Laboratory (June 28, 2011); and Jeffrey Griffin, Savannah River National Laboratory (June 10, 2011).

The national laboratories listed above were provided with a list of relevant disciplines to assist them in providing appropriate demographic data. The disciplines included radiation biology, nuclear forensics, nuclear and radiochemistry, radiation chemistry, separations chemistry, environmental radiochemistry, and actinide and isotope geochemistry, as well as topics associated more with the application of these disciplines, such as actinide chemistry and processing, chemistry of special nuclear materials, nuclear fuel cycle expertise, or dose assessment. Each laboratory provided an analysis of workforce numbers and demographics by age band cohort and level of degree, provided that the committee present the national laboratory data in this report as a compilation. The estimated current numbers of national laboratory career employees with nuclear and radiochemistry skills, according to age cohort and degree, are shown in Figure 2-6. Projected demands for nuclear and radiochemistry related skills at national laboratories based on anticipated terminations, one year and 2-5 years from now, are shown in Table 2-5.

G

Positron Emission Tomography Radiopharmaceuticals

TABLE G-1 Positron Emission Tomography Radiopharmaceuticals

Trade Name	Radiopharmaceutical	Clinical Indication
Ammonia N13	^{13}N-Ammonia	Myocardial blood flow
Cardio-Gen	^{82}Rb-Rubidium chloride	Myocardial blood flow
Florbetapir F18 **	^{18}F-styryl-pyridine	Amyloid Plaques Alzheimer's disease
Fluorbetabane F18[#]	^{18}F-styryl-pyridine	Amyloid Plaques Alzheimer's disease
Flutemetamol F18[#]	^{18}F-hydroxy-benzothiazole	Amyloid Plaques Alzheimer's disease
Fluorpiridaz F18[#]	^{18}F-pyridazinone	Myocardial blood flow
Fludeoxyglucose F18 Injection	^{18}F-Fluorodeoxyglucose	Oncology,Myocardial Viability, Seizure Foci
Sodium Fluoride F18	Sodium ^{18}F-fluoride	Bone scans
Single Photon Emission Computed Tomography (SPECT) Radiopharmaceuticals		
Chromitope Mallinkrodt Cr-51	Sodium ^{51}Cr-chromate	Red Blood Cell Labeling
Ga-67	^{67}Ga-Gallium citrate	Soft tissue tumor, Inflammatory processes
Indium In 111 oxyquinoline	^{111}In-Indium oxyquinoline	Luekocyte and platlet labeling
MPI Indium DTPA In 111	^{111}In-Indium Pentetate disodium	Cerebrospinal fluid kinetics
ProstaScint	^{111}In-Indium Capromab Pendetide	Prostate Tumor
Octreoscan	^{111}In-Indium Pentetreotide	Neuroendocrine tumors Gastroenteropancreatic tumors
Zevalin	^{111}In -Ibitumonmab iuxetan	non-Hodgkin's lymphoma
Sodium Iodide I 123	Sodium ^{123}I-iodide	Thyroid uptake
Datscan	^{123}I-Ioflupane	Striatal Dopaminae Transporters
Adreview	^{123}I-Iobenguane	Pheochromacytoma, Neuroblastoma
Glofil	^{125}I-Iothalamate	Glomerular filtration measurement
Jeanatope	^{125}I-human Serum Albumin	Total blood and plasma volume
Megatope	^{131}I-human Serum Albumin	Total blood and plasma volume
Bexxar	^{131}I-Tositumomab	non-Hodgkin's lymphoma
Sodium Iodide I 123	Sodium ^{123}I-iodide	Thyroid uptake
Technetium Generator Technelite Ultra-Technekow FM	^{99m}Tc-Pertechnetate	Thyroid, salivary and parathyroid glands, ectopic gastric mucosa, dacryocystography, cystography
Neurolite	^{99m}Tc-Bicisate (ECD)	Cerebral Perfusion
Hepatolite-CIS	^{99m}Tc-Disofenin (DISIDA)	Hepatobiliary function
Ceretec	^{99m}Tc-Exametazine (HMPAO)	Cerebral Perfusion

(continued)

TABLE G-1 Continued

Trade Name	Radiopharmaceutical	Clinical Indication
Pulmolite	^{99m}Tc-Aggregated albumin	Pulmonary Perfusion
Technetium Tc 99M Albumin Aggregated Kit		
Choletec	^{99m}Tc-Mebrofenin	Hepatobiliary function
Osteolite	^{99m}Tc-Medronate (MDP)	Bone imaging
Technescan MAG3	^{99m}Tc-Mertiatide	Renal function
Techneplex DTPA	^{99m}Tc-Pentetate	Renal function, Radioaresol ventilation
Phosphotec Pyrolite Pyro Technescan PYP Amersham PYP	^{99m}Tc-Pyrophosphate (PYP)	Infarct imaging, in vivo Red blood cell labeling
Cardiolite Miraluma	^{99m}Tc-Sestamibi	Myocardial blood flow, Breast tumor
DMSA	^{99m}Tc-Succimer (DMSA)	Renal function
Sulfur Colloid	^{99m}Tc-Sulfur Colloid	Liver/spleen gastric emptying, GI bleeds
AN-Sulfur Colloid		
Myoview	^{99m}Tc-Tetrofosmin	Myocardial blood flow
Thallium	^{201}Tl-Thallium chloride	Myocardial blood flow, Parathyroid, Tumor
Xenon	^{133}Xe-xenon gas	Pulmonary ventilation
Radiotherapeutics		
Zevalin	^{90}Y-Ibitumonmab Tiuxetan	non-Hodgkin's lymphoma
Bexaar	^{131}I-Tositumomab	non-Hodgkin's lymphoma
Metastron	^{89}Sr-strontium	bone pain from skeletal metastases
Quadramet	^{153}Sm Lexidronin	bone pain from skeletal metastases
Sodium Iodide I 131	Sodium ^{131}I-iodide	Thyroid therapy
HICON		
Phosphocol 32	^{32}P-Chromicphosphate	Intracavity malignancies

** Conditionally approved by the FDA
# in Phase 3 clinical trials
SOURCE: NRC/IOM 2007; FDA 2011; UAMS 2011

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NRC/IOM (National Research Council and Institute of Medicine). 2007. Appendix C. Commercially available radiopharmaceuticals. Pp. 151-154 in Advancing Nuclear Medicine through Innovation. Washington, DC: The National Academies Press.

UAMS (University of Arkansas for Medical Sciences). 2011. Radiopharmaceutical List and Package Inserts. Nuclear Pharmacology, College of Pharmacy, University of Arkansas for Medical Sciences [online]. Available: http://nuclearpharmacy.uams.edu/resources/PackageInserts.asp [accessed October 24, 2011].

H

Chemistry Department Chairs

TABLE H-1 Alphabetical listing of Institutions and Chemistry Department Chairs among the Top 100 U.S. Chemistry Departments Contacted

Institution	Chair Name
Arizona State University	Petuskey, William
Boston College	Hoveyda, Amir
Brandeis University	Deng, Li
Brigham Young University	Burton, Greg
Brown University	Zimmt, Matthew
California Institute of Technology	Barton, Jacqueline
Carnegie Mellon University	Kim, Hyung
Case Western Reserve University	Barkley, Mary
Colorado State University	Fisher, Ellen
Cornell University	Baird, Barbara
Dartmouth College	Jacobi, Peter
Duke University	Warren, Warren
Duquesne University	Wheeler, Ralph
Emory University	Lynn, David
Florida Institute of Technology	Babich, Michael
Florida State University	Schlenoff, Joseph
Georgetown University	Tong, Yu Ye
Georgia Institute of Technology, Main Campus	Liotta, Charles
Georgia State University	Wang, Binghe
Harvard University	Jacobsen, Eric
Indiana University, Bloomington	Giedroc, David
Johns Hopkins University	Meyer, Gerald
Louisiana State University	Maverick, Andrew
Massachusetts Institute of Technology	Ceyer, Sylvia
Michigan State University	Maleczka, Robert
Mississippi State University	Lewis, Edwin
New York University	Ward, Michael
North Carolina State University at Raleigh	Gorman, Chris
Northwestern University	Ratner, Mark
Ohio State University, Main Campus	Chisholm, Malcolm
Pennsylvania State University	Garrison, Barbara
Princeton University	MacMillan, David
Rensselaer Polytechnic Institute	Breneman, Curt

(continued)

TABLE H-1 Continued

Institution	Chair Name
Rice University	Matsuda, Seiichi
Rutgers University, New Brunswick	Garfunkel, Eric
San Diego State University	Carrano, Carl
Stanford University	Zare, Richard
Stony Brook University	Hsiao, Benjamin
Texas A&M University	Russell, David
University of Akron	Calvo, Kim
University of Alabama	Shaughnessy, Kevin
University of Arizona	Wysocki, Vicki
University of California, Berkley	Neumark, Dan
University of California, Davis	Gervay-Hague, Jacquelyn
University of California, Irvine	Rychnovsky, Scott
University of California, San Diego	Continetti, Robert
University of California, Santa Barbara	Dahlquist, Frederick
University of California, Los Angeles	Courey, Al
University of California, Riverside	Chronister, Eric
University of Chicago	Jordan, Richard
University of Cincinnati	Heineman, Bill
University of Colorado, Boulder	Eaton, Bruce
University of Connecticut	Suib, Steven
University of Florida	Talham, Daniel
University of Georgia	Amster, Johnathan
University of Houston	Hoffman, David
University of Illinois, Chicago	Hanley, Luke
University of Illinois, Urbana-Champaign	Zimmerman, Steven
University of Iowa	Arnold, Mark
University of Kansas	Lunte, Craig
University of Kentucky	Yates, Steven
University of Maryland, Baltimore County	LaCourse, William
University of Maryland, College Park	Doyle, Michael
University of Massachusetts, Amherst	Martin, Craig
University of Michigan, Ann Arbor	Meyerhoff, Mark
University of Minnesota, Twin Cities	Tolman, William
University of Missouri, Columbia	Atwood, Jerry
University of New Mexico	Bear, David
University of North Carolina, Chapel Hill	Redinbo, Matthew
University of Notre Dame	Henderson, Kenneth W.
University of Oklahoma, Norman	Ritcher-Addo, George
University of Pennsylvania	Molander, Gary
University of Pittsburgh	Waldeck, David
University of Rochester	Boeckman, Robert
University of Southern California	McKenna, Charles
University of Southern Mississippi	Heinhorst, Sabine
University of Tennessee	Feigerle, Charles
University of Texas, Austin	Quy, Richard
University of Utah	White, Henry
University of Virginia	Cafiso, David
University of Washington, Seattle Campus	Hopkins, Paul

TABLE H-1 Continued

Institution	Chair Name
University of Wisconsin, Madison	Weisshaar, James C.
Utah State University	Hengge, Alvan
Vanderbilt University	Stone, Michael
Virginia Polytechnic Institute and State University	Merola, Joseph
Washington State University	Hipps, K.W.
Washington University in St. Louis	Buhro, William
Wayne State University	Rigby, James
Yale University	Miller, Scott

SOURCE: NRC 2011

TABLE H-2 Alphabetical Listing of Additional Institution Department Chairs Identified and Contacted for this study

Institution	Department Name	Chair Name
Auburn University	Chemistry and Biochemistry	Ortiz, Joseph
Ball State University	Chemistry	Lang, Patricia
Bucknell University	Chemistry	Clapp, Charles
California State University, Sacramento	Chemistry	Crawford, Susan
Clarkson University	Chemistry and Biomolecular Sciences	Christiansen, Phillip
Cleveland State University	Chemistry	Gates, Michael
East Carolina University	Chemistry	Hicks, Rickey
Florida Atlantic University	Chemistry and Biochemistry	Parkanyi, Cyril
George Washington University	Chemistry	King, Michael
Howard University	Biochemistry and Molecular Biology	George, Matthew
Illinois State University	Chemistry	Baur, John
Indiana University	Chemistry	Reilly, James
Indiana University-Purdue University Indianapolis	Chemistry and Chemical Biology	Siegel, Jay
Jackson State University	Chemistry	Yu, Hongtao
Louisiana Tech University	Chemistry Program	Snow, Lloyd Dale
Loyola University Chicago	Chemistry	Holz, Richard
Marquette University	Chemistry	Ryan, Michael
Middle Tennessee State University	Chemistry	MacDougall, Preston
Northern Illinois University	Chemistry and Biochemistry	Carnahan, Jon
Ohio University	Chemistry and Biochemistry	Malinski, Tadeusz
Old Dominion University	Chemistry and Biochemistry	Gregory, Richard
Pittsburg State University	Chemistry	Siam, Khamis
Polytechnic University	Chemical and Biological Sciences	Garetz, Bruce
Rosalind Franklin University	Chemistry and Molecular Biology	Kaplan, Ronald
Sam Houston State University	Department of Chemistry	Norman, Richard
Sloan-Kettering Institute	Molecular Pharmacology and Chemistry Program	Scheinberg, David
State University of New York, College of Environmental Science and Forestry	Chemistry	Stipanovic, Arthur
Temple University School of Medicine	Biochemistry	Gill, Donald

(continued)

TABLE H-2 Continued

Institution	Department Name	Chair Name
Texas State University, San Marcos	Chemistry and Biochemistry	Brittain, William
Texas Tech University	Chemistry and Biochemistry	Casadonte, Dominick
The Pennsylvania State University, College of Medicine	Biochemistry and Molecular Biology	Bond, Judith
University at Buffalo, The State University of New York	Chemistry	Colon, Luis
University of Alabama at Birmingham	Chemistry	Graves, David
University of Arkansas	Chemistry and Biochemistry	Durham, Bill
University of Central Florida	Chemistry	Belfield, Kevin
University of Delaware	Chemistry and Biochemistry	Theopold, Klaus
University of Idaho	Chemistry	Wandruszka, Ray
University of Louisville	Biochemistry and Molecular Biology	Gregg, Ronald
University of Louisville	Chemistry	Pack, George
University of Miami	Rosenstiel School of Marine and Science	Hynes, Anthony
University of Mississippi	School of Pharmacy Department of Medicinal Chemistry	Cutler, Stephen
University of Mississippi	Pharmacognosy	Ferreira, Daniel
University of Missouri- St. Louis	Chemistry and Biochemistry	Spilling, Christopher
University of Texas at Dallas	Chemistry	Ferraris, John
University of the Sciences in Philadelphia	Chemistry and Biochemistry	Pophristic, Vojiislava
University of Toledo	Chemistry	Pinkerton, Alan
University of Washington	Chemistry	Hopkins, Paul
University of Washington	Medicinal Chemistry	Rettie, Allan
Wayne State University	Chemistry	Rigby, James
Western Illinois University	Chemistry	McConnell, Rose
Yeshiva University, Albert Einstein College of Medicine	Biochemistry	Schramm, Vern
York University	Chemistry	Rudolph, Jochen
Youngstown State University	Chemistry	Mincey, Daryl

SOURCE: ACS 2009.

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NRC (National Research Council). 2011. *Data-Based Assessment of Research-Doctorate Programs in the United States*. J. P. Ostriker, C. V. Kuh, and J. A. Voytuk, Eds; Washington, DC: The National Academies Press. Available online at www.nap.edu/rdp/.

I

Commercial Nuclear Power Plants

TABLE I-1 Alphabetical listing of Nuclear Power Plants and Vendors Contacted and Company Websites

Power Plant	Website
American Electric Power	http://www.aep.com/
Amerenc Corporation	http://www.ameren.com/Pages/Home.aspx
APS (Arizona)	http://www.aps.com/
AREVA*	http://us.areva.com/
Constellation Energy	http://www.cengllc.com/
Constellation Energy	http://www.cengllc.com/
Dionex*	http://www.dionex.com/en-us/markets/power/nuclear-power/lp-72032.html
Dominion	http://www.dom.com/
DTE Energy Company	http://www.dteenergy.com/
Duke Energy	http://www.duke-energy.com/residential.asp
Energy Northwest	http://www.energy-northwest.com/
Entergy	http://www.entergy.com/
Excelon	http://www.exeloncorp.com/Pages/home.aspx
First Energy	https://www.firstenergycorp.com/content/fecorp/fehome.html
Florida Power and Light Co.	http://www.fpl.com/
GE-Hitachi*	http://www.ge-energy.com/products_and_services/products/nuclear_energy/index.jsp
Luminant	http://www.luminant.com/
NextEra Energy	http://www.nexteraenergy.com/
Nebraska Public Power District	http://www.nppd.com/
Omaha Public Power District	http://www.oppd.com/index.htm
Pacific Gas Electric Company	http://www.pge.com/
Progress Energy	https://www.progress-energy.com/
PPL Corporation	http://www.pplweb.com/
Public Service Electric and Gas Company (PSE&G)	http://www.pseg.com/
SCANA Corporation	http://www.scana.com/en/
Southern California Edison-San Onofre Nuclear Generating Station	http://www.sce.com/PowerandEnvironment/PowerGeneration/SanOnofreNuclearGeneratingStation/default.htm?goto=songs
Southern Company	http://www.southernco.com/
South Texas Project Electric Generating Station	http://www.stpegs.com/

(continued)

TABLE I-1 Continued

Power Plant	Website
Tennessee Valley Authority	http://www.tva.gov/
Westinghouse Electric*	http://www.westinghousenuclear.com/
Wolf Creek Nuclear Operating Corporation	http://www.wcnoc.com/
Xcel Energy Services	http://www.xcelenergy.com/

*Nuclear Power Plant Vendor