The Impact of Low-Level Radioactive Waste Management Policy on Biomedical Research in the United States

NATIONAL RESEARCH COUNCIL

The Impact of Low-Level Radioactive Waste Management Policy on Biomedical Research in the United States

Committee on the Impact of Low-Level Radioactive Waste Management
Policy on Biomedical Research in the United States
Board on Radiation Effects Research
Commission on Life Sciences
National Research Council

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PREFACE

The National Research Council's Committee on the Impact of Low-Level Radioactive Waste Management Policy on Biomedical Research in the United States was called on to assess the effects of the low-level radioactive waste management policy on the current and future activities of biomedical research. This report provides an assessment of the effects of the current management policy for low-level radioactive waste (LLRW), and resulting consequences, such as higher LLRW disposal costs and onsite storage of LLRW, on the current and future activities of biomedical research. That assessment will include evaluating the effects that the lack of facilities and disposal capacity, and rules of disposal facilities, have on institutions conducting medical and biological research and on hospitals where radioisotopes are used for the diagnosis and treatment of disease.

The committee members wish to thank several individuals who have contributed to their understanding of the impacts of the current low-level radioactive waste management policy on biomedical research. Louise Ramm of the National Institutes of Health provided valuable and useful historical insights for the committee's study. The committee is especially grateful for the information provided by Frank Castronovo, Carol Marcus, Leonard Smith, James Osborne, Holmes Brown, Kenneth Miller, Richard Fry, Henry Porter, and Edgar Bailey. They were generous with their time and thorough in discussing their impressions of, and knowledge about, the impact of low-level radioactive waste management policy on the current and future activity of biomedical research.

The committee thanks the National Research Council staff who worked with us, especially the study director Dr. Isaf Al-Nabulsi, for keeping the committee focused and assisting in the preparation of several drafts of this report. Dr. Al-Nabulsi was well assisted in the administrative details related to the committee's work by Bridget Edmonds and Doris Taylor.

Sidney H. Golub
Chairman

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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 National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making the 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 participation in the review of this report:

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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 James E. Cleaver, appointed by the Commission on Life Sciences and Charles F. Stevens, appointed by the Report Review Committee, who 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.

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EXECUTIVE SUMMARY

This project, in the National Research Council's Board on Radiation Effects Research, evaluates the impact of the current policy related to low-level radioactive waste (LLRW) management on biomedical research, particularly in universities and medical centers. The objective of this project is to assess the effects of factors such as higher disposal costs and onsite storage on the current and future activities of biomedical research, including the effects of lack of access to disposal facilities on institutions that conduct biomedical research and on hospitals where radionuclides are crucial for the diagnosis and treatment of disease.

Radioactive waste from biomedical research includes laboratory solutions containing radionuclides, counting vials for assessing radioactivity, biological materials such as tissue-culture cells and animal carcasses, and materials that come into contact with radioactive substances, such as glass or plastic containers, gloves, paper and other absorbent materials for containing spills, and filters. Diagnostic and therapeutic patient-care procedures can also generate radioactive waste. The management of these wastes typically follows a series of steps. First, most of these materials contain short-lived radioactive materials and are stored for decay to essentially nonradioactive materials before being disposed of as nonradioactive waste. Second, remaining radioactive materials are typically managed using methods such as compaction, supercompaction, or incineration. Finally, products of these treatment processes are disposed of as LLRW in local landfills as authorized by specific license conditions.

This report of the Committee on the Impact of Low-Level Radioactive Waste Management Policy on Biomedical Research in the United States, summarizes what is known and not known about the impact of policy regarding LLRW management on biomedical researchers. In addition to assessing the severity of the problem, the report, to the extent possible, identifies techniques that some institutions have used to solve problems and highlights methods that have been and are used successfully to reduce the volumes of LLRW and mixed waste. The report also describes the changes that are occurring in laboratories regarding the use of radioactive and nonradioactive methods and ascertains the impact of these changes on research outcomes and LLRW policy.

The recurring theme of this report is that the major driver of biomedical-LLRW management is cost. When disposal was inexpensive, it was used and pretreatment of waste was not as common. When disposal became expensive, there was a shift to a greater use of alternatives, such as storage for decay (although this practice had been in use for some time), volume reduction including compaction, supercompaction, and incineration, and the use of nonradioactive materials in biomedical applications. These methods of LLRW management are appropriate, safe, and environmentally sensitive. The committee heard no evidence of environmental emergencies resulting from current policies. However, the management of LLRW by biomedical generators is becoming very expensive. Furthermore, the costs to manufacturers of radioactive materials and radiopharmaceuticals will likely increase if these suppliers are required to dispose of radioactive materials. The costs for managing LLRW will be passed on to the purchasers of their products. As costs mount, additional research funds are expected to be diverted to LLRW management. The biomedical research effort cannot indefinitely absorb a continuously and sharply increasing cost of this service. Eventually, some other approach must be found to contain these costs. Understanding the economic basis of LLRW management is a key factor in developing policy that can be sustained and used for planning. In general, economic factors drive the choices in LLRW management, and economic factors need to be incorporated into policy development.

The committee concluded that the current situation is manageable but expensive. Continuing inflation of LLRW costs at the current rate of increase could interfere with research efforts, and in particular, with the management of LLRW costs as a component of overhead. New technologic developments in nuclear medicine diagnostic and treatment procedures and in molecular biology tracer methodologies could result in a substantial increase in use of radioactive materials. The possibility of an unscheduled and arbitrary closure of one of the remaining disposal facilities is a risk that would force generators to respond quickly with alternative management strategies for LLRW. This will be seriously disruptive, and it will take regulatory or political will and user support to respond and perhaps prevent such an occurrence.

It is important to understand that the process of LLRW disposal management policy must make financial sense. Therefore, the committee recommends that institutions engaged in biomedical research carefully assess their LLRW management practices for cost effectiveness. Furthermore, the committee recommends that funding agencies modify their support mechanism for infrastructure costs to pay their fair share of the cost of LLRW management and disposal. Agencies engaged in the support of biomedical research need to take into consideration that the costs of radioactive-waste management, a necessary component of research, have risen sharply in recent years. The regulatory environment for the biomedical research community is complex; any efforts that the regulatory community could make to simplify or streamline the regulatory requirements for managing LLRW without compromising worker or public health and safety would be a benefit.

The committee recommended that institutional efforts to promote the use of appropriate alternatives to radioactive materials for research are useful and should be commended and strongly encouraged.

The biomedical research community has adapted to the changes that have occurred thus far in LLRW access and cost. However, the committee has no assurance that additional stresses on the system will be as well tolerated over the longer term.

1

INTRODUCTION

The National Research Council Committee on the Impact of Low-Level Radioactive Waste Management Policy on Biomedical Research in the United States was asked to assess the effects of the current management policy for LLRW, and resulting consequences, such as higher LLRW disposal costs and onsite storage of LLRW, on the current and future activities of biomedical research. The committee heard from researchers, state and institutional officials, and radiation safety officers regarding the effects of the existing LLRW disposal situation, including the effects of the lack of access to disposal facilities on institutions that conduct biomedical research and on hospitals where radionuclides are crucial for the diagnosis and treatment of disease.

BACKGROUND OF THIS REPORT

For the last 20 years, many groups—including generators of LLRW, environmental groups, elected state officials, radiation-safety officers, and private citizens—have been engaged in the difficult and often contentious problem of what to do with LLRW. Efforts to site and open new disposal sites for LLRW are deadlocked. Although there has been concern among stakeholders about the continuation of access to reasonably priced disposal capacity, the current system, which uses the existing capacity has posed no health or safety issue.

Currently, three facilities accept LLRW for disposal in the United States. They are in Barnwell, South Carolina, Richland, Washington, and Clive, Utah. If access to disposal facilities were to be interrupted, LLRW targeted for disposal would add to the waste that has already accumulated in temporary storage facilities in numerous hospitals and universities across the United States. Research organizations would probably continue to find ways to reduce, treat, and store their LLRW for the near term, but with some unknown level of added costs and management challenges. Interruption of access to disposal sites would necessitate the expansion of temporary storage facilities that are in common use today for decay of short-lived materials.

These practices have been followed and improved since the 1980s when costs of managing LLRW increased dramatically and disposal sites began to close. Biomedical researchers in particular are facing increasing disposal charges. In addition, LLRW wastes are sometimes mixed with chemicals, such as volatile solvents or exhibit the characteristics of hazardous materials as defined under federal law, Resource Conservation and Recovery Act (RCRA) (40 CFR 261, subpart C) (USEPA, 2000). Although the biomedical community does not generate a large amount of mixed waste, it nevertheless, presents unique and difficult challenges.

The increasing costs of biomedical research LLRW management, including concern for continued disposal facility access to storage and disposal sites, costs of developing or expanding storage and treatment, and costs of disposal should be expected to continue to have effects on the use of radioactive materials for diagnosis and treatment of disease and for research. Alternatives to using radioactive material will most likely be selected more often, and longer-lived radioactive materials could become less desirable to use.

The waste-disposal plan set in motion in 1980 by Congress in the Low-Level Radioactive Waste Policy Act (LLRWPA, Public Law 96-573) and the Low-Level Radioactive Waste Policy Amendments Act of 1985 (LLRWPAA, Public Law 99-240) charged the states with the responsibility for LLRW disposal and gave them the right to form regional compacts with other states to share a disposal facility. By 1998, 42 states had formed 10 compacts. Seven unaffiliated states, the District of Columbia, and Puerto Rico remained individually responsible for their radioactive waste (LLW Forum Summary Report, 1998). However, no state or compact is actively developing a site, and it is not clear whether a new site will open soon. Nonetheless, all generators currently have access to disposal. Long-term access to disposal facilities, however, is uncertain. The development of future disposal capacity poses complex problems of public education and acceptance, financial costs, and the need for the capacity. Capacity (available disposal space in licensed disposal sites) has never been at issue with respect to LLRW, but access to existing capacity at manageable costs has been.

This report of the Committee on the Impact of Low-Level Radioactive Waste Management Policy on Biomedical Research in the United States, was commissioned to assess impacts of future access to the current LLRW-disposal capacity on biomedical research. In assessing the current LLRW management policy, one needs to recognize that the LLRW controversy is overwhelmingly focused on the nuclear-power industry. The amount of biomedical LLRW, measured in volume, is less than 5-10% of the total LLRW disposed, and the quantity of radioactive materials disposed is no more than a few percent of the total disposed and generated in the US (OTA, 1989; Fuchs, 1999). Public policy regarding LLRW tends to focus on the nuclear-power aspect of the question, so biomedical research is likely to continue to struggle to find ways to adapt to the policy and regulatory environment dictated by the nuclear-power debate.

The current policy of biomedical-LLRW disposal creates several burdens. One is on regulators, who must oversee a widely distributed system. Storage-for-decay facilities have been successfully operated in conformance with regulations in many states and at many institutions; but as they become more numerous and the types and quantities of wastes managed become more varied and larger, the challenge for regulators to inspect and to ensure conformance with requirements will increase.

Another burden is on research institutions, which have to fund and maintain facilities for storage and disposal of LLRW. Most academic institutions pass some or all of the direct costs for LLRW disposal to investigators via recharges. When this is the case, these costs compete directly with other research activities of the investigator.

Furthermore, the administrative infrastructure to support waste disposal programs (oversight committees, administrative staff, etc.) is generally supported by the administrative overhead component of indirect costs charged to grants. This component is within the capped portion of federal indirect cost calculations (OMB Circular A-21, 2000), thus limiting the institutional capacity to find additional resources to build these programs.

It is crucial to understand that the process of LLRW-disposal management policy must make financial sense. The current economic model evolved on the bases of the use of short-lived radionuclides except ^{14}C (carbon-14) and ^{3}H (tritium). If use of radionuclides increases substantially because of the larger national commitment to biomedical research or because of the introduction of new radionuclide-dependent assays or methods, or if the use of longer-lived radionuclides increases for any reason, the current system will be challenged. Policy and regulatory bodies need to understand the economic basis of LLRW-disposal policy if they are to modify the system in the event of major new needs.

Although disposal capacity appears to be sufficient for the biomedical needs of the next several decades, the future of commercial-LLRW management policy in the United States is by no means guaranteed. Considering the costs and the political and technical processes necessary to license a facility, new capacity is unlikely to develop quickly. However, research trends are not predictable, and some unforeseen technology might require the introduction of new radioactive materials or increased use of such materials. That possibility is worrisome because our nation is unprepared for a substantial change in the current situation.

BACKGROUND TO LLRW-MANAGEMENT POLICY

Radioactive materials contribute in important ways to biomedical research, medical diagnosis and therapy, and industrial and academic activities. For example, radioactive materials are used in biomedical research for the analysis of physiologic and biochemical processes, gene sequencing, enzyme reactions, and pharmacokinetic and cellular process studies. The most commonly used radionuclides for the above example are ^{32}P (phosphorus-32), ^{33}P (phosphorus-33), ^{3}H, ^{14}C, ^{35}S (sulfur-35), and ^{45}Ca (calcium-45). ^{125}I (iodine-125) is used for radioimmunoassay, protein metabolism, hormone, and anatomical imaging studies. Microspheres labeled with ^{46}Sc (scandium-46), ^{57}Co (cobalt-57), ^{85}Sr (strontium-85), ^{95}Nb (niobium-95), ^{113}Sn (tin-113), ^{153}Gd (gadolinium-153), and ^{141}Ce (cerium-141) are used for regional blood-flow studies. ^{60}Co (cobalt-60), ^{67}Ga (gallium-67), ^{99m}Tc (technetium-99m), ^{125}I, ^{123}I (iodine-123), ^{131}I (iodine-131), ^{192}Ir (iridium-192), and ^{201}Tl (thallium-201) are used in medical diagnosis and therapy (Miller, 2000, CORAR, 1993). Diagnosis of primary tumors, early detection of metastasis, and studies of metabolic functions such as thyroid function are a few examples (Miller, 2000). New technologies for diagnosis and therapy are being developed, such as more sophisticated imaging techniques and monoclonal-antibody therapies that combine radioactive materials with molecules that target specific diseases. LLRW produced in those biomedical uses of radioactive materials, although smaller in volume and radioactivity than reactor-produced LLRW, requires treatment, transportation, and disposal.

LLRW is defined by exclusion. It is radioactive waste that is not high-level radioactive waste (HLRW), not spent nuclear fuel, and not transuranic waste (TRU). Nor does LLRW include uranium-mill tailings waste, naturally occurring radioactive material (NORM), or technologically enhanced NORM (TENORM). LLRW does include everything from very short-lived to very long-lived radionuclides. It includes any radioactive wastes generated from the use of source, byproduct, or special nuclear material that is not in one of the categories listed above. Biomedical LLRW includes residual unused radioactive materials, laboratory solutions containing radioactive materials, counting vials, and animal carcasses containing injected materials; gloves, swipes, and other items that are used during injection in a hospital or clinic; and filters, centrifuge tubes, pipettes, and laboratory trash used during research involving radioactive materials.

LLRW generated in biomedical research is typically of small volume and low radioactive content compared with that generated in the nuclear-power industry, but there are exceptions. Some wastes generated in nuclear power plants, such as housekeeping wastes, contain small quantities of radioactive material in large volumes; and some medical wastes, such as that from manufacturing facilities used to generate medical radionuclides, can contain higher quantities of radioactive material in smaller volumes. Overall, the biomedical-research and medical communities generate small volumes of LLRW containing small quantities of radioactive materials, compared with the nuclear-power industry materials that must be managed under the same regulations.

Because of the increasing costs associated with LLRW disposal and interruption of access for disposal, some generators and researchers have faced difficulties in disposing of their radioactive waste. As a result, effective steps have been taken to decrease volumes of LLRW. The reduction in disposed volumes of LLRW and activities from biomedical institutions in the last 15 years is shown in Table 1. Biomedical-research institutions have made provisions to manage their LLRW in a manner that will assure no disruption to research. Their methods include:

- Reevaluation of research needs and techniques.
- Selection, where possible, of short-lived radioactive materials and avoidance of long half-life radionuclides so that wastes generated can be managed by storage for decay.
- A combination of waste-generation avoidance, compaction, and incineration.

Table 1. Summary of Disposed Volumes and Activities of Low-Level Radioactive Waste Generated by Medical and Biomedical Research Institutions in the United States[a]

Year	Medical Generators		Academic Generators	
	Volume, ft^3	Activity, Ci	Volume, ft^3	Activity, Ci
1986	27,698.03	23.21	41,799.84	107.23
1987	33,963.24	24.31	58,565.76	68.46
1988	24,170.63	86.56	49,372.54	2,282.73
1989	34,730.20	149.32	66,101.42	1,946.44
1990	22,792.13	59.45	48,555.10	1,096.04
1991	28,622.20	70.03	48,047.94	472.13
1992	26,341.24	397.77	44,248.45	1,724.27
1993	4,953.30	21.08	11,850.83	110.25
1994	5,011.77	454.93	17,793.55	420.97
1995	1,923.78	6.13	7,537.68	47.72
1996	2,192.43	11.22	14,191.24	60.80
1997	1,280.56	10.40	7,446.45	61.04
1998	1,456.31	9.98	4,904.79	132.12
1999	970.01	4.93	10,110.92	43.42
2000	147.14	2.79	5,440.70	46.06

[a] Data from http://mims.inel.gov/web/owa/gentype.report. Time period: January 1, 1985 through September 30, 2000.

Compaction by the generators is encouraged by disposal rates that are based on volume of material. There is no apparent fast-approaching limit on capacity for burial of LLRW that is driving prices. However, there is a physical limit to how much compaction can be accomplished, and further development of this approach must await significant advances in technology. It cannot be determined how this situation might change if a disposal site were closed, although it seems likely that the cost of disposal at remaining open sites would encourage further use of compaction.

This situation is an example of a number of potential problems in disposal that cannot be analyzed at present because too many variables are unknown. Other such potential issues include the possible loss of public confidence if there should be a fire or other untoward event at a disposal site, public reaction to a large increase in radioactive materials that are being stored for decay in research institutions, changes in reimbursement rates for medical procedures that use radioactive materials, or upper limits on the cost for disposal of LLRW that makes either research or medical use of these materials economically impractical. The committee was interested in these questions, but could only speculate on answers to the questions. The committee did note the efforts of radiation safety officers to provide plans for dealing with major problems such as natural disasters in order to minimize health and safety risks under such circumstances.

Over the last 2 decades, there has been success in minimization and improvement in the management of LLRW disposal at several biomedical institutions (Castronovo, 2000, Miller, 2000, Osborne, 2000), and LLRW volumes have been reduced. For example, volumes of ^{32}P and ^{33}P, ^{35}S, ^{125}I, ^{3}H, and ^{14}C waste generated at NEN Life Science Products, Inc., were reduced by 50% from 1989 to 1994; and generation of radioactive waste per unit of radiopharmaceutical product has decreased by about 15% per year (Todisco and Smith, 1995).

Storage for decay is one of the methods used to minimize the volume of waste that will require disposal. There is a financial incentive to minimize waste volume: every dollar spent on disposal is a dollar that cannot be spent on research. The US Nuclear Regulatory Commission allows decay in storage of radioactive materials that have a half-life less than 120 days (USNRC 1999a; Ring et al., 1993; Emery et al., 1992; Edwards et al., 1996; Party and Gershey 1989). Volume reduction by filtration, ion-exchange reverse osmosis, and evaporation are used for aqueous wastes (Bohner et al., 1983; Edwards et al., 1996) and adsorbers or scrubbers are used to retain radioactive gases to optimize for storage of those materials for decay (Miller et al., 1979). Solidification is sometimes used, but it increases the volume of LLRW that must be disposed of.

Animal carcasses pose a particular problem because freezing them until radioactivity decays is acceptable only for carcasses that contain short-lived radionuclides (King et al., 1988; Tries et al., 1996). For those with longer-lived radionuclides, incineration at a licensed offsite disposal facility is the only solution; again, this adds to the cost of dealing with the waste. Other techniques have been developed, including chemical digestion (Kaye et al., 1993), dry distillation (Saito et al., 1995), and freeze-drying (Hamawy, 1995). ^{14}C and ^{3}H in liquid scintillation fluids and animal carcasses can be considered nonradioactive if their concentration is less than 0.05 μCi per gram [10CFR20.2005 (USNRC 1999a)].

It is convenient to divide *LLRW* into categories, as set forth below.

A. Medicine

Diagnosis

In nuclear medicine and imaging procedures, radionuclides that have half-lives of 6-73 hours, such as ^{99m}Tc and ^{201}Tl, are used because of their imaging characteristics, and because they are short-lived and do not result in a high dose to the patient compared to the diagnostic benefit of the test. They do not contribute to the volumes of LLRW needing permanent disposal. They are stored for decay typically at the point of generation and then disposed in accordance with the requirements for nonradioactive constituents of the waste.

Positron-Emission Tomography (PET) is an important diagnostic tool. PET scans permit assessment of metabolic functions and are useful in various medical situations, including brain and heart disorders and the need to detect early metastases. Procedures involving PET scans use radionuclides with half-lives of less than 2 hours, such as ^{15}O (oxygen-15), ^{18}F (fluorine-18), and ^{13}N (nitrogen-13). Because of the short half-lives, PET does not pose problems in LLRW management.

Treatment

Many of the radionuclides, such as ^{131}I, ^{90}Sr (strontium-90), ^{153}Sm (samarium153), and ^{90}Y (yttrium-90), used in the treatment of cancer and other diseases do not result in waste that has to be sent to LLRW disposal sites. Monoclonal antibodies tagged with various radionuclides are coming into wider use. ^{131}I-tagged monoclonal antibodies are currently being used in clinical trials for the treatment of non-Hodgkin's lymphoma and other malignant diseases. For inpatient treatment of thyroid diseases, small amounts of 131I wastes are generated and patient excreta may enter into the sanitary sewer as well. These wastes are generally stored for decay.

Wastes are generated at medical radiopharmaceutical-manufacturing facilities, such as those that make the ^{125}I seeds used in cancer treatment and the manufacturers of radionuclides used in basic and applied medical research. These manufacturer wastes do need to be managed, often with treatment and disposal as LLRW. If disposal costs result in a decreased usage of certain radionuclides and products, the continued manufacture of these materials could be at risk.

Sealed sources, such as ^{60}Co, used in cancer therapy may be recycled and do not often go directly to disposal sites. Recycling or disposal decisions, managed by the manufacturers, are generally based on comparative economics for the cost or remanufacturing and later the market value of the sealed source. Although still in use in some facilities, ^{60}Co is not as popular as large electron accelerators for primary cancer radiotherapy in the United States.

B. Biomedical Research

Radioactive waste from biomedical research is dominated by comparatively short-lived radionuclides, but some long-lived radionuclides, mainly ^{3}H and ^{14}C, are commonly used in laboratories. A substantial portion of ^{3}H and ^{14}C is managed with direct disposal, incineration, or disposal into sanitary sewers according to 10 CFR 20.2003. The radiopharmaceutical companies that supply the materials for biomedical research generate some LLRW. Specific data on generation rates in the radiopharmaceutical industry were not available to the LLRW committee. However, it is probably safe to assume that this component of the LLRW stream will retain its current proportional relationship to the amount of LLRW generated by research and medical uses. If, for example, there is a great increase in the use of radioactive materials attached to anti-cancer pharmaceuticals, then the industrial, research, and medical generations of LLRW will all increase concordantly.

C. Nuclear Power Plants

Wastes from nuclear power plants differ substantially from the biomedical-research, medical, and industrial waste in the radioactive materials produced and the amounts (in volume and radioactive material quantity) to be managed. Nuclear power facilities generate all three classes of LLRW as defined in 10 CFR 61, which are termed Class A, Class B, and Class C. Each successive class has larger concentration limits for long- and short-lived radionuclides. Class B and Class C are subject to stability requirements for waste form and waste packages that must be met by disposal-site operators. Wastes associated with routine maintenance are typically Class A wastes, which are treated by compaction, supercompaction, or incineration. Consolidated wastes from those processes are disposed of at licensed LLRW facilities. Water-processing operations, such as coolant-water cleanup, tend to generate higher concentrations of radioactive materials in wastes, including ion-exchange resin and other solid wastes. Irradiated hardware removed from reactor cores is typically highly radioactive and contains, for example, ^{60}Co, ^{63}Ni (nickle-63), and ^{55}Fe (iron-55). These are almost always Class C wastes.

2

CHARACTERISTICS OF LOW-LEVEL RADIOACTIVE WASTE

Waste characterization is the determination of the radiological, chemical and physical properties of waste to establish the need for treatment, handling, processing, storage, or disposal of radioactive materials. Typically, characterization is helpful in assessing what must be done to meet the requirements regarding transportation and disposal of radioactive waste.

Radiological waste characterization involves quantifying and detecting the radiation characteristics for the principal radionuclides used in clinical and biomedical research and found in hospital and research-institution waste.

Chemical waste characterization involves the determination of chemical components and properties. It can be accomplished by analyzing waste samples or on the basis of knowledge of the process that generated the waste.

Physical waste characterization involves inspection to determine physical form (solid, liquid, or gas) and other physical properties such as dispersability, and other properties such as compressive strength that might be needed to meet disposal requirements.

Some LLRW contains hazardous materials as defined in 40 CFR 261 (USEPA, 2000). Such LLRW is called mixed waste. Hazardous wastes are defined as wastes that are toxic, corrosive, flammable, or reactive. Mixed waste is regulated as LLRW under 10 CFR 61, and as hazardous waste under 40 CFR 261 (USEPA, 2000). A 1990 survey which profiled commercially generated low-level mixed waste (NUREG/CR-5938), indicated that 140,000 ft^3 of mixed wastes was generated in the United States (data from http://www.epa.gov/radiation/mixed-waste/nat_prof.htm) during that one year. This current generation rate is not related to inventories of mixed waste generated from past generation. Typically, the annual amount of mixed waste generated by the commercial sector which included the biomedical users as small contributors, is much smaller than the amount generated by the Department of Energy. Several effective steps have been taken by generators to reduce the amount of mixed waste (CORAR, 1993).

3

CHALLENGES TO THE BIOMEDICAL INVESTIGATOR

REGULATION

Biomedical research that uses radioactive materials operates in a highly regulated environment. Three agencies regulate LLRW: the US Nuclear Regulatory Commission (USNRC), the Environmental Protection Agency (EPA), and the Department of Transportation (DOT). The US Nuclear Regulatory Commission, under its authority from the Atomic Energy Act of 1954 and amendments, regulates the use of source, byproduct, and special nuclear material. It has delegated its authority to over 35 states, which are known as "agreement states". Agreement states retain the authority to regulate everything except nuclear power and other reactors regardless of location and to regulate special nuclear material in quantities over 350 grams. The regulations of the agreement states must be compatible with those of the US Nuclear Regulatory Commission. EPA develops general standards for radiation protection of the general public. DOT regulates the shipment of LLRW and all radioactive materials. Other federal and state agencies regulate and provide guidance on the use and control of radiation-producing devices and radioactive material. For example, the US Geological Survey has been involved in the High-Level Waste Repository Project at Yucca Mountain, and the US Postal Service regulates traffic of radioactive materials through the US mail system.

Disposal of radioactive materials is governed by the Code of Federal Regulations 10 CFR 20.2001-20.2006 (USNRC, 1991a) and by 10 CFR Part 61.1-61.84 (USNRC, 1983). These regulations are quoted verbatim here, as understanding these regulations is central to understanding the nature of the disposal issue. The regulations specify:

(a) A licensee shall dispose of radioactive materials:

(1) By transfer to an authorized recipient as provided in 20.2006 or in the regulations in parts 10 CFR 30, 40, 60, 61, 70, or 72;
(2) By decay in storage;
(3) By release in effluents within the limits in §20.1301; or
(4) As authorized under 20.2002, 20.2003, 20.2004, or 20.2005.

(b) A person must be specifically licensed to receive waste containing licensed material from other persons for:

(1) Treatment prior to disposal;
(2) Treatment or disposal by incineration;
(3) Decay in storage;
(4) Disposal at a land disposal facility licensed under 10 CFR 61; or
(5) Disposal at a geologic repository under 10 CFR 60.

A licensee or applicant for a license may apply to the Commission for approval of proposed procedures, not otherwise authorized in the regulations in this chapter; to dispose of licensed material generated in the licensee's activities, each application shall include:

(a) A description of the waste containing licensed material to be disposed of, including the physical and chemical properties important to risk evaluation, and the proposed manner and conditions of waste disposal;
(b) An analysis and evaluation of pertinent information on the nature of the environment;
(c) The nature and location of other potentially affected licensed and unlicensed facilities; and
(d) Analyses and procedures to ensure that doses are maintained ALARA[a] and within the dose limits in this part.

Provisions for disposal by release into sanitary sewerage are prescribed in 10 CFR 20.2003 and provide that:

(a) A licensee may discharge licensed material into sanitary sewerage if each of the following conditions is satisfied:

(1) The material is readily soluble (or is readily dispersible biological material) in water;
(2) The quantity of licensed or other radioactive material that the licensee releases into the sewer in 1 month divided by the average monthly volume of water released into the sewer by the licensee does not exceed the concentration listed in table 3 of Appendix B to part 20; and
(3) If more than one radionuclide is released, the following conditions must also be satisfied:

(i) The licensee shall determine the fraction of the limit in table 3 of Appendix B to part 20 (USNRC, 1991b) represented by discharges into sanitary sewerage by dividing the actual monthly average concentration of each radionuclide released by the licensee into the sewer by the concentration of that radionuclide listed in table 3 of appendix B to 10 CFR part 20; and
(ii) The sum of the fractions for each radionuclide required by paragraph (a)(3)(i) of this section does not exceed unity; and

(4) The total quantity of licensed and other radioactive material that the licensee releases into the sanitary sewerage system in a year does not exceed 5 curies (185 GBq) of hydrogen-3, 1 curie (37 GBq) of carbon-14, and 1 curie (37 GBq) of all other radioactive materials combined.

(b) Excreta from individuals undergoing medical diagnosis or therapy with radioactive material are not subject to the limitations contained in paragraph (a) of this section.

Treatment or disposal by incineration are provided in 10 CFR 20.2004 which prescribe that:

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[a] As low as reasonably achievable

(a) A licensee may treat or dispose of licensed material by incineration only:

(1) As authorized by paragraph (b) of this section; or
(2) If the material is in a form and concentration specified in 10 CFR 20.2005; or
(3) As specifically approved by the Commission pursuant to 10 CFR 20.2002.

(b)

(1) Waste oils (petroleum derived or synthetic oils used principally as lubricants, coolants, hydraulic or insulating fluids, or metalworking oils) that have been radioactively contaminated in the course of the operation or maintenance of a nuclear power reactor licensed under 10 CFR 50 may be incinerated on the site where generated provided that the total radioactive effluents from the facility, including the effluents from such incineration, conform to the requirements of Appendix I to 10 CFR 50 and the effluent release limits contained in applicable license conditions other than effluent limits specifically related to incineration of waste oil. The licensee shall report any changes or additions to the information supplied under 10 CFR 50.34 and 50.34a of this chapter associated with this incineration pursuant to 10 CFR 50.71 of this chapter, as appropriate. The licensee shall also follow the procedures of 10 CFR 50.59 of this chapter with respect to such changes to the facility or procedures.
(2) Solid residues produced in the process of incinerating waste oils must be disposed of as provided by 10 CFR 20.2001.
(3) The provisions of this section authorize onsite waste oil incineration under the terms of this section and supersede any provision in an individual plant license or technical specification that may be inconsistent.

Provisions for disposal of specific wastes most commonly found in the biomedical and research communities are provided in 10 CFR 20.2005:

(a) A licensee may dispose of the following licensed material as if it were not radioactive:

(1) 0.05 microcurie (1.85 kBq), or less, of hydrogen-3 or carbon-14 per gram of medium used for liquid scintillation counting; and
(2) 0.05 microcurie (1.85 kBq), or less, of hydrogen-3 or carbon-14 per gram of animal tissue, averaged over the weight of the entire animal.

(b) A licensee may not dispose of tissue under paragraph (a)(2) of this section in a manner that would permit its use either as food for humans or as animal feed.
(c) The licensee shall maintain records in accordance with 10 CFR 20.2108.

Provisions for transfer for disposal and manifest for radioactive waste 10 CFR 20.2006:

(a) The requirements of this section and Appendix G to 10 CFR Part 20 are designed to:

(1) Control transfers of low-level radioactive waste by any waste generator, waste collector, or waste processor licensee, as defined in this part, who ships low-level waste either directly, or indirectly through a waste collector or waste processor, to a licensed low-level waste land disposal facility (as defined in 10 CFR Part 61);

(2) Establish a manifest tracking system; and
(3) Supplement existing requirements concerning transfers and record keeping for those wastes.

(b) Any licensee shipping radioactive waste intended for ultimate disposal at a licensed land disposal facility must document the information required on US Nuclear Regulatory Commission's Uniform Low-Level Radioactive Waste Manifest and transfer this recorded manifest information to the intended consignee in accordance with Appendix G to 10 CFR Part 20.
(c) Each shipment manifest must include a certification by the waste generator as specified in Section II of Appendix G to 10 CFR Part 20.
(d) Each person involved in the transfer for disposal and disposal of waste, including the waste generator, waste collector, waste processor, and disposal facility operator, shall comply with the requirements specified in Section III of Appendix G to 10 CFR Part 20.

General provisions, for compliance with environmental and health protection regulations are provided in 10 CFR 20.2007. Nothing in this subpart relieves the licensee from complying with other applicable federal, state, and local regulations governing any other toxic or hazardous properties of materials that may be disposed of under this subpart.

In summary, US Nuclear Regulatory Commission and Agreement State licensees that store mixed waste must comply with the regulations under the Resources Conservation and Recovery Act (RCRA). Specific guidance is available in NRC/EPA Draft Storage Guidance (available: http://www.epa.gov/radiation/mixed-waste/mw_p27.htm). EPA has extended its policy of non-enforcement of RCRA section 3004(j), “Storage Prohibition at Facilities Generating Mixed Radioactive/Hazardous Waste”, until October 31, 2001 (BRER staff personal communication with Nancy Hunt, 2000), for facilities generating mixed waste for which there is no available option for treatment or disposal. The policy recognized that treatment and disposal options for such mixed wastes were limited, and it recognized that ultimate treatment and disposal for some materials might not occur within the 90-day treatment time required.

DISPOSAL COST

The direct costs for disposing of LLRW have risen sharply in the last 25 years from about \$1/ft^3 to around \$400/ft^{3,} and projected costs for new sites suggest further increases to well over \$1,000/ft^3 (Ryan and Newcomb, 2000).

Table 2 shows the disposal fees for the Barnwell site, operated by Chem-Nuclear and now owned by GTS Duratek. Permission was obtained from Henry Porter to publish

Table 2. Disposal Fees for Barnwell Facility—Effective July 1, 2000 (Porter, 2000)

Base Disposal Charges: Standard and Special-Nuclear-Material Waste	**from "Uniform Schedule of Maximum Disposal Rates for Atlantic Compact Regional Waste"**	**from "Disposal Rate Schedule for Non-Atlantic Compact Waste"**
Weight – Density Range	*Atlantic Compact Rate*	*Non-Atlantic Compact Rate*
Equal to or greater than 120 lbs./ft^3	$ 4.40 per pound	$ 4.40 per pound
Equal to or greater than 75 lbs./ft^3 and less than 120 lbs./ft^3	$ 4.84 per pound	$ 4.84 per pound
Equal to or greater than 60 lbs./ft^3 and less than 75 lbs./ft^3	$ 5.94 per pound	$ 5.94 per pound
Equal to or greater than 45 lbs./ft^3 and less than 60 lbs./ft^3	$ 7.70 per pound	$ 7.70 per pound
Less than 45 lbs./ft^3	$ 7.70 per pound times the ratio of 45 lbs./ft^3 divided by package density	$ 7.70 per pound times the ratio of 45 lbs./ft^3 divided by package density
Millicurie Charge	$ 0.33 per millicurie (b.1) *or* $0.66 per millicurie for radionuclides with greater than 5-year half lives (b.2) *Option b.1 will apply unless generator specifically elects option b.2 for all of its shipments at the beginning of a fiscal year* maximum millicurie charge is $132,000/shipment	$0.36 per millicurie maximum millicurie charge is $144,000/shipment
Base Disposal Charges: Biological Waste	$1.00 per pound in addition to above rates	$1.00 per pound in addition to above rates
Dose Rate Surcharge *Dose Level*	*Atlantic Compact Multiplier of Base Weight Rate*	*Non-Atlantic Compact Multiplier of Base Weight Rate*
0 mR/hr - 200 mR/hr	1.00	1.00
>200 mR/hr - 1 R/hr	1.08	1.08
>1R/hr - 2R/hr	1.12	1.12
>2R/hr - 3R/hr	1.17	1.17
>3R/hr - 4R/hr	1.22	1.22
>4R/hr - 5R/hr	1.27	1.27
>5R/hr - 10R/hr	1.32	1.32
>10R/hr - 25R/hr	1.37	1.37
>25R/hr - 50R/hr	1.42	1.42
>50R/hr	1.48	1.48
Irradiated Hardware Charges (applicable only where shipment requires shut-down of other disposal operations) *Includes irradiated cask-handling fee.*	$50,000.00 per shipment	$50,000.00 per shipment
Special Nuclear Material Surcharge	$10.00 per gram	$10.00 per gram
Atlantic Compact Commission Administrative Surcharge	$4.00 per cubic foot *Subject to change during year*	$4.00 per cubic foot *Subject to change during year*
	Underliningindicates a difference	

the latest site availability charge for the Barnwell facility (Porter, 2000). Base charges range from about $350/ft^3$ to above $500/ft^3$, depending on weight. Table 3 shows the rate schedule for the Richland site[a] . Richland site availability charges are in the range of $20-27/ft^3$ per year, depending on volume and radiation levels. Additional charges include volume, shipment, container, and exposure charges, which can vary substantially. For example, a 100-ft^3 shipment with 500-mR/h exposure would cost about $100/ft3; storing this shipment for 20 years would cost about $600/ft^3$ (undiscounted). Table 4 shows the current charges for disposal of biomedical LLRW at the Richland facility.

Disposal is only one component of the total cost of LLRW management. It is instructive to examine two cases of radioactive-waste management activities. The first is in a university setting (Osborne, 2000), the second is in a research-hospital setting (Miller, 2000). Both cases were presented to the committee.

Osborne provided the following information regarding annual LLRW management costs at the University of Iowa:

1. Disposal	$62,000
2. Support staff	Three staff members in the Radiation Protection Office, part of whose duty is LLRW management
3. Storage facility	16,000 ft^2 building, about half of which is used for LLRW storage
4. Faculty	part of whose time is spent on several committees

To obtain an approximate estimate of the total annual cost of LLRW management, we make some conservative (low-end cost) assumptions. If we estimate the average salary and fringe benefits of each of the support staff at $40,000 and if we assume that they spend about 50% of their time on LLRW management, the annual staff-support cost would be $60,000.

The annual cost of the storage facility can be calculated by using the square-footage cost for a leased building, for example, $10/ft^2$ per year. That would mean $80,000 per year for half the 16,000-ft^2 facility.

Faculty time and its equivalent cost are more difficult to estimate. The University of Iowa has four committees related to radiation protection with a total of some 20 members (Osborne, 2000). Assuming that members spend, on the average, 10 days per year on committee duty, and that 50% of this duty is related to radioactive-waste management, 100 person-days of faculty time would be spent on radioactive-waste management. With an average salary of $80,000 and 200 days of academic-year work, that would mean another $40,000 per year.

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[a] The committee does not have data from Envirocare of Utah. The Envirocare facility does not publish a rate schedule due to the range of radioactive and mixed waste licenses and the diversity of the needs of Envirocare's customers.

Table 3. Site Availability Charge for Richland Facility—Effective May 1, 2000[a]

SITE AVAILABILITY CHARGE

	Rates	
Block	Block Criteria	Annual Charge per Generator
0	No site use at all ....$	100
1	Greater than zero but less than or equal to 10 ft^3 and 50 mR/h	211
2	Greater than 10 ft^3 or 50 mR/h * but less than or equal to 20 ft^3 and 100 mR/h *	404
3	Greater than 20 ft^3 or 100 mR/h * but less than or equal to 40 ft^3 and 200 mR/h *	776
4	Greater than 40 ft^3 or 200 mR/h * but less than or equal to 80 ft^3 and 400 mR/h *	1,491
5	Greater than 80 ft^3 or 400 mR/h * but less than or equal to 160 ft^3 and 800 mR/h *	2,868
6	Greater than 160 ft^3 or 800 mR/h * but less than or equal to 320 ft^3 and 1,600 mR/h *	5,513
7	Greater than 320 ft^3 or 1,600 mR/h * but less than or equal to 640 ft^3 and 3,200 mR/h *	10,597
8	Greater than 640 ft^3 or 3,200 mR/h * but less than or equal to 1,280 ft^3 and 6,400 mR/h *	20,372
9	Greater than 1,280 ft^3 or 6,400 mR/h * but less than or equal to 2,560 ft^3 and 12,800 mR/h *	39,167
10	Greater than 2,560 ft^3 or 12,800 mR/h * but less than or equal to 5,120 ft^3 and 25,600 mR/h *	75,288
11	Greater than 5,120 ft^3 or 25,600 mR/h *	143,234

* For purposes of determining the site availability charge, mR/h is calculated by surmuing the mR per hour at container surface of all containers received during the year.

[a] Permission was obtained from US Ecology, Inc. to publish the latest site availability charge for Richland facility (personal communication with Arvil Crase, 2000).

Table 4. Current Charges For Biomedical Low-Level Radioactive Waste At US Ecology's Richland Facility—Effective May 1, 2000[a]

COMPONENT	**RATE**	**UNITS**	**TOTAL**
Site availability fee	$10,597.00	BLOCK 7	$ 10,597.00
Volume (cu ft)	22.90	500.00	$ 11,450.00
Shipments	4,228.00	1	$ 4,228.00
Containers	1,449.00	5	$ 7,245.00
Dose rate/container (mR/hr at container)			
<200	16.00	5	$ 80.00
>200 - <1,000	1,150		$ -
>1,000 - <10,000	4,550		$ -
>10,000 - <100,000	6,950		$
>100,000	116,500		$ -
TOTAL US ECOLOGY			$ 33,600.00
TAXES & FEES			
(1) PERPETUAL CARE FEE	$ 1.75	500.00	$ 875.00
(2) B & O TAX	3.3%	33,600.00	$ 1,108.80
(3) SITE SURVEILLANCE	6.00	500.00	$ 3,000.00
(4) SURCHARGE	6.50	500.00	$ 3,250.00
(5) WUTC FEE	1.00%	33,600.00	$ 336.00
TOTAL TAXES & FEES			$ 8,569.80
TOTAL CHARGES			$ 42,169.80

(1) Perpetual care fee - $1.75 per ft^3
(2) B & O Tax - 3.45% of US Ecology charges
(3) Site surveillance - $6.00 per ft^3
(4) Surcharge - $6.00 per ft^3
(5) WUTC fee - 1.0 % of US Ecology charges

Assumptions: 500 ft^3, 1 shipment 5 containers under 200 mR/hr Dose

The average charge for disposal of biomedical LLRW from 1996-1999 is $47.00 per ft^3

[a] Permission was obtained from US Ecology, Inc. to publish current charges for biomedical low-level radioactive waste at US Ecology's Richland facility (personal communication with Arvil Crase, 2000).

Using those assumptions, the total annual cost of radioactive-waste management at this institution would be \$242,000, of which \$62,000, or 26% would be for disposal itself. The University of Iowa produces about 20,000 kg (44,000 lb) of radioactive waste per year. The overall management costs thus translate into \$5.50/lb. Depending on the density of packing, that could be between \$275/ft^3 (at 50 lb/ft^3) and \$550/ft^3 (at 100 lb/ft^3). Because most of our assumptions are conservative, those estimates are probably a lower bound of the actual costs attributable to radioactive-waste management.

Data provided by Miller for the Hershey Medical Center at Pennsylvania State University tell a similar story. His estimates of annual costs are as follows:

1. Employee	\$57,577
2. Disposal	\$36,500
3. Disposal supplies	\$ 2,800
4. Storage space	1,505 ft^2

Again assuming \$10/ft^2 per year for the storage facility, we estimate a total of about \$112,000/year, of which about 33% is for disposal itself. That does not include faculty time, which could not be estimated on the basis of data available to the committee.

The total annual volume of radioactive waste at the Hershey Center is 33,270 lb. Thus, the annual cost for radioactive waste management is \$3.37/pound. Again assuming a range of 50-100 lb/ft^{3,} this translates into \$168/ ft^3 to \$337/ft^{3,} respectively.

That superficial cost analysis clarifies two issues. First, the overall annual cost to the generating institutions for radioactive-waste management is not insignificant. Although perhaps small relative to the revenues generated by the research or other activities that create the waste, it is likely to be an important portion of the institutions' overhead income associated with these activities. It would displace the use of overhead income for other competing purposes. The problem is compounded by Office of Management and Budget Circular A-21, which limits recovery of the administrative component of overhead to 20% of direct costs. Rising costs for radioactive-waste disposal are included in a category with rising costs for animal care, human-subjects protection, and other complex compliance issues; and revenues to reimburse such cost are constrained by federal policy. This situation throws some of the costs for radioactive-waste management directly on to the institution in competition with other research priorities.

Second, the disposal component of the costs is substantial (26-33% of total annual cost for the two sites described above). This suggests that longer-term onsite storage may be cost-beneficial, at least for the short-lived radionuclides, as illustrated by the following simple calculation. If storage space is leased at \$10/ft^2 per year and if a 100 ft^2 area can hold 500 ft^3 of radioactive material (piled 10 ft high, but using only 50% of the space to allow for space between packages and access), the cost of storage would be \$1,000/year for 500 ft^3 of material or \$2/ft^3 per year, or \$40/ft^3 for 20 years. That is well below the cost of disposal at the Barnwell or Richland site. Even including other waste-management costs, the annual costs of long-term onsite storage are likely to be lower than the cost of permanent disposal.

ACCESS TO DISPOSAL

Legal Framework

In the early 1970s, six commercial LLRW disposal sites in the United States handled the needs of industrial, utility, medical, and research waste producers. By 1978, three had closed, and the governors of the three states with remaining operating sites, Nevada, South Carolina, and Washington, put the rest of the country on notice that they wanted the other states to take responsibility for their own waste. With the strong backing of the National Governor's Association, the National Conference of State Legislatures, and most state governments, Congress reacted by passing the LLRWPA (Public Law 96-573) in 1980.

The act gave the states responsibility for ensuring adequate disposal capacity for commercial LLRW generated within their borders, except for waste generated by federal weapons or research and development activities. It also encouraged states to enter into multistate compacts to manage the waste safely and efficiently on a regional basis, subject to congressional approval, and it allowed a compact region to exclude low-level waste generated outside the region from its disposal site after January 1, 1986.

However, because of the difficulty that states were experiencing in siting new facilities as the 1986 deadline approached, Congress passed the LLRWPAA of 1985 (Public Law 99-240), effective January 15, 1986. That act includes incentives and penalties to prod states and regions without disposal sites to build new disposal facilities. In addition, the three states with existing sites were to remain open to all states through December 1992. Waste producers could be denied access to existing sites if their states were not making adequate progress toward building disposal facilities.

Current Status of Disposal

In spite of the incentives and penalties for States under the Low-Level Radioactive Waste Disposal Policy Amendments Act, which have not been enforced, no new sites have opened. The Beatty, Nevada site, which was the first commercial disposal site to open, was closed in 1993 after 30 years of operation, and a site in Utah, operated by Envirocare, opened in 1991. All states have access to one or more of the existing disposal sites in Washington, Utah, and South Carolina.

The Richland site, in Washington, opened in 1965 and operated by US Ecology, is restricted for use by the states of the Northwest Compact and Rocky Mountain Compact. Washington, Oregon, Idaho, Montana, Utah, Wyoming, Alaska, and Hawaii are in the

Northwest Compact; Nevada, Colorado, and New Mexico are in the Rocky Mountain Compact. The site is expected to remain open until 2056. Recently, the Northwest Compact approved a resolution reflecting its continuing support for the 1985 Low-Level Radioactive Waste Policy Amendments Act and urging other states and compacts to provide disposal capacity (LLRW Management Summary Report, 1999).

The Barnwell, South Carolina, site, opened in 1971 and operated by Chem-Nuclear, and now owned by GTS Duratek, receives Class A, B, and C waste from most of the rest of the nation.

The Tooele County (Clive), Utah, site, opened in 1991, receives only Class A LLRW. Envirocare of Utah, the site operator has applied for a license expansion to allow it to include Class B and C wastes.

Testing the System: Closures of Barnwell

In trying to visualize future constraints on the LLRW management system, we can look at what has happened when access to facilities has been denied.

The Barnwell site has been the only site to which almost all states have had access for most of the 30-year period when new sites were to have been built and opened. However, Michigan and North Carolina were denied access to it because they were not making progress toward building new disposal sites. Barnwell was also closed to all out-of-compact waste from July 1, 1994, to July 1, 1995, in anticipation of the site closure when North Carolina was to open its new site for the Southeast Compact.

Michigan

Michigan, which was the first host state for the Midwest Compact's LLRW disposal facility, was denied access to Barnwell from 1991 to 1996 because of lack of progress in developing the facility. During that time, generators apparently were able to store their waste (LLW Forum Summary Report, 1998).

At the University of Michigan, for example, waste was minimized and substitutes were used for long-lived radionuclides were methods employed to reduce the volume and radioactivity of the waste produced. Waste segregation was also used (BRER staff personal communication with Tim Cullen, University of Michigan Hazardous Materials Management, 1998). With these changes, it was possible to maintain the research effort.

Smaller institutions, such as smaller colleges and pharmaceutical companies, have eliminated the use of nonessential radioactive materials; such as for teaching purposes, but lack of sufficient storage space is a problem for them (BRER staff personal communication with Thor Strong, Michigan representative to LLRW Forum, 1998).

Larger facilities—such as hospitals, research institutions, and industry—use onsite storage and have modified practices rather than eliminating them. Health-care facilities apparently did not have a problem with storing their relatively small amounts of therapeutic and diagnostic waste. However, they are concerned about the long-term implications of adding waste-storage costs to waste-disposal costs.

North Carolina

North Carolina, which was to have opened the Southeast Compact's disposal facility after the Barnwell facility was scheduled to close, was denied access to Barnwell in 1998 because of lack of progress in developing the facility. It regained access in July 2000.

North Carolina's response was similar to Michigan's. Generators used one or more of the following: changing radioactive-material processes, minimizing waste, increasing storage capacity for LLRW, looking for other disposal options, reducing volume, buying waste compactors for onsite use, and storing waste until another disposal option became available (Fry, 2000).

As in Michigan, most large generators in North Carolina have capacity to store their own waste or have built new storage facilities. One of the large generators, the University of North Carolina at Chapel Hill, stores short-lived waste for decay, but ships long-lived waste to GTS Duratek (formerly Scientific Ecology Group-SEG) for volume reduction through incineration. However, because North Carolina did not have access to Barnwell, the ashes were sent back to North Carolina for storage until access to a disposal facility was regained. Although the waste volume was reduced, there was an additional cost for storing the waste that would not have been incurred if they had been able to ship the ash for disposal.

The University's branches cannot use Chapel Hill's storage facility, because Chapel Hill is not licensed as a waste processor and disposal facility, so storage-to-decay poses a problem for them. They also have fewer personnel to handle the waste (BRER staff personal communication with Bob Wilson, Director, Radiation Safety, 1998). Principal investigators at Chapel Hill were apparently relatively unaffected by the lack of access to Barnwell because steps were taken to alleviate problems, such as an aggressive volume-reduction effort. The cost of disposing of longer-lived radionuclides has forced investigators to use nonradioactive substitutes. East Carolina University, the fourth-largest university generator, stores short-lived wastes to decay and sends some short-lived wastes to Envirocare. Incineration is the primary means of disposal of long-lived waste. It also ships to GTS Duratek for reduction, although a vigorous onsite volume-reduction program has been successful. Substitution of nonradioactive material has not been promoted (BRER staff personal communication with Daniel Sprau, Director, Radiation Safety, 1998).

Smaller pharmaceutical companies were forced to seek alternatives to disposal at Barnwell, including finding ways to increase the efficiency or size of onsite storage and using their own storage, treatment, or other disposal facilities. Researchers continued to use both radionuclides and other methods of detection, such as fluorescence. Some waste processing and storage facilities were available, but long-term storage was a problem. Envirocare is not an option for smaller generators, because of its volume requirements, radioactivity-concentration limits, and other restrictions.

North Carolina generators managed their waste by a combination of processing and treatment options and disposal at the Envirocare facility. Most are using brokers to package their waste for shipment for out-of-state processing or disposal. However, there is concern about the future. If access to out-of-state processing and disposal facilities were restricted, most generators would soon have to create more storage capacity; some generators stated that they could store waste for only a few months before having to add capacity (North Carolina Radiation Protection Survey by phone, 1999).

Barnwell Disposal Site Closure: 1994-1995

When the Barnwell facility was closed to all out-of-compact states from July 1, 1994, to July 1, 1995, an estimated 3,000 companies and institutions that were using radioactive materials and generating LLRW in 31 states were affected. Organizations United, a radioactive-materials users organization, sponsored a survey to ascertain the likely consequences if new facilities were not opened to replace the Barnwell facility (Organizations United Report, 1996).

From a list of companies and institutions that had sent low-level waste to disposal facilities in the recent past, 680 LLRW managers were randomly selected to be interviewed from February 1995 through early July 1995. They included 271 research companies, 212 medical institutions, 54 government facilities, and 39 electric companies. The survey verified that without access to a disposal facility, managers mobilize a variety of resources to manage the waste problem temporarily, but that long-term effects would be more difficult to manage.

Many of those companies and institutions who foresaw adverse effects if lack of access to offsite disposal continued for another 5 years (to the year 2000) were in the health field. Five medical institutions had been forced to refer patients to other facilities because of cuts in diagnostic procedures. Another 30 said that they would probably have to refer patients elsewhere if the situation continued for another 5 years.

A majority of the institutions had already incurred higher operating costs, and some reported a loss of revenue.

Most companies or institutions had made physical, structural, or personnel adaptations, such as adding or expanding onsite storage equipment and space and adding or reassigning personnel to manage radioactive materials onsite. Most of them already had waste-minimization and volume-reduction programs in place, but 103 companies or institutions initiated these programs after they lost access to disposal.

Only 33 companies or institutions discontinued the use of radioactive materials altogether. Some were able to eliminate some uses, and some made at least some substitutions. However, 37 of them said the change increased the cost of their services and/or had a negative effect on the quality of their services.

Nearly three-fourths of those surveyed considered loss of disposal access to be a major problem. Among the reasons cited were inadequate onsite storage capacity, increased potential for environmental and safety problems, and adverse effects on consumers.

Changes – Barnwell and Envirocare

Two recent developments will affect access to disposal sites for states not in the Northwest Compact states of Washington, Oregon, Idaho, Montana, Utah, Wyoming, Alaska, and Hawaii; the Rocky Mountain Compact states of Nevada, Colorado, and New Mexico; or the Atlantic Compact states of South Carolina, New Jersey, and Connecticut.

South Carolina recently passed legislation that established the three-state Atlantic Compact and would eventually close the Barnwell facility to all out-of-compact states except New Jersey and Connecticut, formerly the Northeast Compact (South Carolina Compact Law – A357, R376, S1129). Of the remaining 3 million cubic feet of capacity at Barnwell, up to 800,000 ft^3 is reserved for waste from New Jersey and Connecticut. (The compact commission could revise the estimate of need downward by unanimous consent.) After 2008, the Barnwell facility will no longer accept out-of-compact waste. The Barnwell facility's schedule is as follows (Porter, 2000):

2001 – 160,000 ft^3 2002 – 80,000 ft^3 2003 – 70,000 ft^3 2004 – 60,000 ft^3
2005 – 50,000 ft^3 2006 – 45,000 ft^3 2007 – 40,000 ft^3 2008 – 35,000 ft^3

Furthermore, although the legislation allows the compact commission to vote to admit new member states to the compact, a state seeking admission to the compact would be required to host a new regional disposal facility.

In Utah, Envirocare has applied for permits and licenses to accept Class B and Class C wastes in addition to the Class A waste that it is now licensed to accept. It has received approval from the Tooele County Commission to accept Class B and C waste, but it must still receive siting and license approval from the Utah Division of Radiation Control and approval from the governor and the legislature in its next session, which begins in January 2001 (Israelsen, 2000).

If Envirocare's license expansion is approved, an option to dispose of Class B and Class C waste other than at Barnwell would be open to generators throughout the nation, but it might be especially attractive to those in western states. Some potential users of the site have said that they do not and will not send their LLRW to Envirocare, because of possible liability problems related to how the site has been operated. Any generator that has used the site might be considered a responsible party if the site becomes a Superfund site. Cost might also enter the picture, depending on the disposal rates set by Envirocare.

Although it is certain that there will be no access to Barnwell for most states in the near future, it is not certain that the Envirocare facility will become available or acceptable to all LLRW generators. That uncertainty makes long-term planning for LLRW disposal difficult.

4

ADAPTATIONS AND WASTE MINIMIZATIONS

OVERVIEW

Institutions have adopted several techniques to reduce waste volume and improve in the management of LLRW disposal, including:

- Increasing the capacity for onsite storage for decay.
- Increasing the use of nonradioactive alternatives.
- Limiting the number of authorized users.
- Reducing in the amount of waste shipped.

Hospitals and academic institutions have been storing radioactive materials onsite for decay for many years as access to disposal sites has become more limited. In general, these materials are stored for decay until no appreciable radioactivity is detectable (usually 10 half-lives) and then disposed of as ordinary trash. Operating such a facility means higher operation costs for user institutions: for finding and preparing space for decay storage, maintenance, training, and recordkeeping and for the use of other space for other productive purposes. Therefore, institutions must provide, adequate funds for facility management. The current policy of biomedical-LLRW disposal makes the problem of waste disposal more prominent because it exists in almost every research facility.

It is more difficult to store long-lived LLRW onsite for decay. Hospitals and academic institutions ship these materials offsite for decay. For example, the University of Iowa ships an estimated 20% of its *LLRW* away for treatment and disposal (Osborne, 2000).

Nonradioactive alternatives have become increasingly accepted in biomedical research as a result of the lack of access to disposal facilities, the expense associated with radioactive-waste disposal, and limitation on space for disposal by decay in storage (Castronovo, 2000; Osborne, 2000). The use of nonradioactive materials in biomedical research is one approach to waste minimization.

IMPROVED MANAGEMENT

There are three key strategies for improved management of LLRW: avoidance, consolidation, and volume reduction. They are all used to minimize the amount of LLRW that needs to be managed, treat wastes to minimize the volume of waste that ultimately need to be disposed of, and create final waste forms that are improved for long-term confinement of contained radioactive material once disposed.

Avoidance is a systematic method for the use of radioactive material that generates a minimum of waste. Careful techniques, segregation of contaminated and noncontaminated materials, and careful decontamination of materials and storage for decay followed by disposal as nonradioactive materials are all common.

In consolidation, LLRW is collected and undergoes minimal treatment before disposal. This approach might be the best for generators that produce only small amounts of waste or produce waste infrequently. Brokerage services are available to provide consolidation for small generators; many of them are in the biomedical research and academic communities. Brokers then provide more economical treatment for these larger consolidated quantities of waste, including incineration, supercompaction, and ultimate disposal.

Volume reduction focuses on reducing the volume of radioactive waste that needs to be treated and disposed. Treatment has costs, as does transportation of materials to and from processors and to disposal. The following section describes a generalized method that is commonly used to guide decision-making in the selection of treatment and disposal options.

A decision to dispose of waste directly or to process it before disposal is principally an economic decision. For the biomedical-waste generator, decisions to proceed with treatment and disposition, including disposal and recycling can be governed by simple relationships (Appendix A). For example, it might be more economical to dispose of waste directly rather than treating it first. If the treatment results in an insufficient volume decrease, the cost of treatment plus the cost of disposal of an insufficiently reduced volume might exceed the original cost of disposal of the untreated waste. Conversely, it might be necessary to treat LLRW to make it acceptable for disposal.

STORAGE PRACTICES

Storage of LLRW generated by biomedical research facilities uses specialized packaging that provides protection from radiation emitted by the waste and isolates the radioactive material from employees handling it. Storage is used to hold LLRW for decay to background levels of radioactivity before disposal as conventional nonradioactive material at conventional or industrial landfills disposal facilities or, for very small LLRW generators, to hold it until sufficient LLRW is accumulated to fill a disposal container or to warrant shipment. LLRW storage for treatment or disposal can occur at the site where the LLRW was generated, offsite at the location of a broker or processor, at a storage facility, or at an LLRW disposal facility before disposal.

Restrictions set by the US Nuclear Regulatory Commission or by individual agreement states limit the types and quantifies of radionuclides that may be stored onsite. Because the license period is confined to the time in which only short-lived material can decay to background levels of radiation, all waste contaminated with radionuclides of longer-lived material must eventually be sent to a disposal site. Because of the unavailability of regional disposal facilities throughout the country, the commission recently extended its allowance for onsite storage without a specific maximum (USNRC, SECY-94-198, 1994).

TREATMENT PRACTICES

Because of concerns over the lack of available disposal facilities in the states that do not have guaranteed long-term access to LLRW disposal sites and the costs associated with disposal, biomedical-research generators of waste continue to pursue more comprehensive and sophisticated methods of treating their LLRW and mixed waste to minimize the volumes and radioactivity of waste requiring disposal in licensed facilities. Numerous practices are used by biomedical researchers to reduce the volume of the typical waste forms generated and to reduce or eliminate radioactivity. These practices are:

a) Centrifugation. This treatment process removes suspended solids by using rotating equipment that depends on centrifugal force to separate solids from liquids.
b) Compaction and supercompaction. Compaction is one of the easiest and most effective treatment techniques in use to reduce dry solid LLRW. Depending on the type of machine, forces range from 10 tons (older, conventional compactors) to 5,000 tons (supercompactors). Resulting waste density ranges from tens to approximately a hundred pounds/ft^3. Metal materials can range up to several hundred pounds/ft^3.
c) Crystallization. This evaporation-related volume-reduction method precipitates solids out of liquid LLRW. The loss of water results in a more concentrated slurry of radioactive material than conventional evaporation and thereby reduces the volume of radioactive liquid waste that requires disposal. The vaporized water can be condensed and discharged or reused in the company or institution's processes.
d) Decontamination. This technique removes radioactive contaminants from the surface or near surface of objects—such as walls, floors, tools, and equipment—or from fluids. Decontamination is achieved by the transfer of contaminants to any of a number of decontamination solutions, including alkaline permanganate, detergents, mineral acids, organic acids, chelating compounds, and water or steam under high pressure. Sand blasting and electropolishing are also used successfully.
e) Dewatering. This technology uses pumps or gravity to draw water from wet solids through filer devices.
f) Drying. Various types of drying processes use heat to remove liquid and form a dry solid. Dryers include the “fluidized-bed,” “in-drum,” and “spray” types.

g) Evaporation. This frequently used volume-reduction technique removes water from radioactive material by using heat to evaporate, and thereby remove, relatively pure water. The original waste stream becomes more concentrated in waste constituents and smaller in volume, and the vaporized water can be reused or discharged.

h) Filtration. This is the process of removing solid particles from LLRW fluids by forcing the fluids through a permeable material with gravity, pressure, or vacuum. The solids suspended in the fluids can be lodged within the pores of the filter or build up on the surface as a filter "cake".

i) Flocculation. This process gathers small particles of waste suspended in liquid waste into larger particles or clusters. Certain chemicals added to the liquid waste can aid this process.

j) Incineration. Incinerating LLRW can achieve waste volume-reduction factors ranging from 30-100 before final ash immobilization and packaging or disposal in a local landfill as provided by license conditions if the radioactivity concentration in the ash does not exceed the concentrations of 10 CFR 20 Appendix B, Table 2 Column 2. After packaging, the volume reduction continues to be up to five times greater than any other minimization technology, including supercompaction.

k) Ion exchange. The process used to separate dissolved solids from liquids by using chemical resins to exchange the atoms in the radioactive materials with the atoms attached to the resin material. This waste separation technique can reduce the level of radionuclides in liquid waste by a factor of 10-100.

l) Polymerization. This chemical process solidifies liquid and wet solid waste by encapsulating small particles or droplets of waste in an irreversibly hardened polymer matrix. Because polymeric systems do not require water to solidify, they can result in some volume reduction.

m) Precipitation. This technique removes dissolved solids from a liquid, and transforms them into a solid waste form.

n) Recycling. This volume-reduction practice is widely used to enable the repeated reuse of decontaminated or slightly contaminated materials and waste. Tools and equipment, and some radioactive sources, can be recycled for repeated use. Recycling involves a combination of other treatment technologies and practices, including segregation, filtration, ion-exchange, evaporation, crystallization, flocculation, precipitation, sedimentation, dewatering, and decontamination.

o) Sedimentation. Gravity, not chemicals, provides the vehicle to remove suspended particles from liquid through the process of sedimentation. Sedimentation, flocculation, and precipitation are often used together to produce a smaller volume of wet solids, which can be separated from any bulk liquid.

p) Segregation. Waste segregation can achieve significant decreases in the volume ultimately requiring disposal. Paper, cloths, and other waste products are frequently discarded as radioactive waste when they are not contaminated with radioactive substances. Reductions in LLRW volume can also be achieved by segregating short-lived from longer-lived waste. Before the concern over availability and cost of LLRW disposal, many research facilities sorted out their waste once before packaging and shipping it for disposal. Such a sorting procedure was able to segregate radioactive from nonradioactive waste. However, it could not segregate long-lived from short-lived waste or separate mixed waste into various treatability groups. Now that those generators in many parts of the country face the potential loss of access to disposal, research institutions are requiring additional minimization procedures of their researchers. Procedures include comprehensive and repeated training of generators, improving waste-identification procedures, reducing the quantities of radioactive materials ordered and used in research, automating procedures to enhance reproducibility, recycling chemicals where possible, repurifying for reuse, preventing the unnecessary generation of mixed waste, and planning the costs and amounts of waste disposal in the design of experiments and products.

q) Shredding. Paper, cloth, plastics, and some light metals can be shredded to aid in compaction and incineration.

r) Solidification. This process mixes materials (cement, asphalt, vinylesterstyrene, and so on) with LLRW as it is placed in disposal containers so that it becomes a solid block.

s) Stabilization. This process is accomplished by using many of the treatment technologies described here, including incineration, solidification, and polymerization. Waste stability is required by Nuclear Regulatory Commission disposal regulations [10 CFR Part 61] to ensure that the waste does “not structurally degrade and affect overall stability of the site through slumping, collapse, or other failure of the disposal unit and thereby lead to water infiltration” (Part 61.56(b)) and to ensure that it will maintain its physical dimensions and its form under disposal conditions, such as the presence of moisture and microbial activity, and activities internal to the waste package, such as radiation effects and chemical changes. Stabilizing LLRW also helps to limit exposure of anyone who inadvertently intrudes onto the disposal site after all institutional controls have ended, at least 100 years after operations cease.

t) Storage for decay. This method provides for the onsite or offsite storage of LLRW with relatively short half-lives to allow some or all of its radioactivity to decay to lower radioactivity levels. Once the activity in the waste has decayed to levels that are indistinguishable from background (at least 10 half-lives), the waste is in effect no longer radioactive and can be safely disposed of as ordinary trash. LLRW generators are building their own decay-in-storage facilities and not only are holding short-lived wastes—for example, ^{125}I, ^{99}Mo (molybdenum-99), ^{201}Tl, ^{67}Ga, ^{32}P and ^{33}P—for decay, but are holding longer-lived wastes—such as ^{3}H, ^{60}Co, and ^{137}Cs (cesium-137)—for partial decay before they are shipped for disposal. Such partial decay can allow a generator to use the Envirocare lower-cost disposal site in Utah (Envirocare of Utah, Inc., License No. UT 2300249).

LLRW DISPOSAL PRACTICES

Disposal of waste is its isolation from the biosphere. The US Nuclear Regulatory Commission definition assumes that LLRW will be isolated by “emplacement in a land disposal facility”, meaning that it will be buried. Some states, however, define disposal slightly differently to allow for isolation in engineered vaults or above ground canisters. A number of disposal practices are used for disposal of LLRW, including that generated by biomedical research facilities. *Near-surface disposal* is defined in 10 CFR 61 as disposal within the upper 30 meter of the earth's surface. This type of disposal facility is operated at Barnwell, South Carolina; Richland, Washington; and Clive, Utah. It is also called engineered *shallow land burial.* Waste containers shipped to the Barnwell disposal site are placed into concrete overpack in engineered trenches. These concrete containers are tightly packed to minimize void spaces and to provide a stable base on which to construct a permanent cap. The cap includes a plastic cap covered by a series of barriers that are designed to retard the infiltration of precipitation down to the surface of the disposal cells. The resulting increase in surface runoff is handled through a specially designed management system. After disposal operations end and throughout the institutional control period after the site is closed, a formal post-closure-monitoring plan will be put into place by the custodial agency of South Carolina. Closure activities are fully funded by an institutional-care fund developed from fees charged to waste generators and an interest-bearing account controlled by South Carolina.

At the Richland site, with less annual rainfall, waste containers are placed in engineered trenches. The containers are backfilled to minimize void spaces and to provide a stable base on which to construct a permanent cap appropriate for the environmental conditions of the facility. The Richland site has capacity to operate through 2063 (BRER staff personal communication with Arvil Crase from US Ecology, Inc., 2000). In contrast, LLRW accepted for disposal at the Envirocare site can be removed from its packaging and mixed with soil before emplacement into a disposal cell. Other wastes and debris are controlled in size and are also placed directly into the landfill (www.envirocareutah.com).

- Case-by-case exemption. A limited exemption to allow the onsite burial of LLRW can be granted to an individual licensee, case-by-case basis, “to dispose of licensed material in a manner not otherwise authorized” in Nuclear Regulatory Commission regulations (10 CFR 20.2002). The rule requires a licensee to submit an application describing the licensed material for which the exemption is sought; kinds, and levels of radioactivity; the proposed manner and conditions of disposal; an analysis of the nature of the environment and use of groundwater and surface waters in the general area; the nature and location of other potentially affected facilities; and procedures to minimize the risk of unexpected or hazardous exposures. About 40 exemptions have been granted nationwide since this rule became effective. After the Commission promulgated its LLRW disposal regulations in 1983 (10 CFR 61), it began discouraging LLRW generators from using onsite burial.

- Disposal to sewer systems. Commission regulations prohibit the discharge of licensed material into sanitary-sewer systems except for very small quantities that are assumed to be diluted by the volume of sewage flowing through the system. The rule prohibits any licensee from using the sewer system to dispose of more than a combined total of all radioactive materials of 1 Ci/year with the exceptions of ^{14}C and ^{3}H. Up to 1 Ci of ^{14}C, and up to 5 Ci of ^{3}H per year may be released into the sanitary-sewer system (10 CFR 20.2003). An exemption within the regulation enables hospitals to use the sewer system for disposal of radioactively contaminated human waste from people undergoing medical diagnosis or treatment with radioactive materials.
- Exempt quantities. Minute quantities of certain radionuclides do not have to be disposed of in licensed LLRW disposal sites under 10 CFR 20.2005 of the regulations. This rule allows the disposal, as nonradioactive waste, up to 0.05 μCi of ^{3}H or ^{14}C in liquid scintillation fluids and up to 0.05 μCi of the same two radionuclides per gram of animal tissue (averaged over the weight of the entire animal).
- Release in effluents. The US Nuclear Regulatory Commission allows radionuclides in radioactive materials or LLRW to be released in effluents (air or water) as long as the release remains within the radiation dose limits allowed by Commission regulations. These limits, if inhaled or ingested continuously over the course of a year, would produce a total effective dose equivalent of 50 mrem (Appendix B of 10 CFR 20).

MINIMIZING THE USE OF RADIOACTIVE MATERIALS

Minimizing the radioactivity in LLRW before its generation by biomedical research and other users of radioactive materials is called source minimization. The biomedical research industry and other radioactive-material users have been successful in their source-minimization and waste-volume-reduction efforts and have become more knowledgeable about minimization objectives and strategies because of the economics of disposal of larger amounts of radioactive material and larger volumes of waste.

EPA also has a volume-reduction policy concerning its regulation of the hazardous components of mixed waste. EPA's requirement directs mixed-waste generators to “have a program in place to reduce the volume and toxicity of waste generated to the extent that is economically practical” (40 CFR 260-261) (USEPA, 2000).

LLRW generated as a result of biomedical research generally is disposed of as compacted trash or solids, institutional laboratory or biologic waste, absorbed liquids, animal carcasses, and sealed sources. Source-minimizing and volume-reducing technologies include compaction and supercompaction, incineration, segregation, storage for decay, and substitution.

Another incentive for the move to minimize waste has been the problem of dealing with mixed waste. Stringent requirements adopted by EPA in response to the 1985 amendments to RCRA require that all mixed waste be treated before it is disposed of (40 CFR 261, subpart C). However, treatment options are not available for all mixed waste. Some low-activity mixed waste can be treated and disposed of at the Envirocare site in Utah; some—up to 0.05 picocurie/g of material containing ^{3}H and ^{14}C—can be incinerated as fuel. As a result, mixed-waste generators must store this waste on site until treatment is available. But such storage is prohibited under the RCRA amendments except for the purpose of accumulating sufficient quantities to treat or dispose. EPA recently moved to modify its regulations to allow mixed waste to be stored for decay on site. Once the activity of the mixed waste has decayed, it can be disposed of as chemical waste; the legal term is “hazardous waste”. The confusion between US Nuclear Regulatory Commission and EPA regulations, as they pertain to mixed waste, has caused many generators to use various source-minimization and waste-volume reduction techniques to avoid generating mixed waste or to treat it and destroy the hazardous chemical properties so that the waste can be disposed of as LLRW.

Efforts by biomedical researchers and other users of radioactive materials to reduce LLRW volumes have been highly successful. Disposal volumes that exceeded 3.7 million cubic feet in 1980 have declined to below 0.5 million cubic feet today (National Low-Level Waste Management Program, 2000). While some LLRW generators remain hesitant to ship their LLRW to the Envirocare disposal site due to concerns over future legal liability, many other generators are shipping large volumes of low-activity LLRW to that site.

Similar efforts to minimize the radioactivity of LLRW shipped for disposal have not produced as dramatic or as consistent a decline in activity in disposed waste. For example, the total activity in all waste shipped for disposal in 1986 was 233,740 curies, which increased to 1,000,102 curies in 1992, decreased to 334,563 curies in 1998, and increased again to 1.8 million curies in 1999 (LLW Notes, 2000). The last rise was due to the disposal of high-activity LLRW from the decommissioning of nuclear power plants.

The difficulty in minimizing radioactivity in LLRW is due to the very nature of volume-reducing processes, which typically do not minimize or eliminate the radioactivity, but rather concentrate it in a smaller volume of waste.

Reducing or eliminating radioactive sources and minimizing or eliminating LLRW are not simple tasks, and complex tradeoffs are involved in designing and implementing such policies. Because the LLRWPA (Public Law 96-573, 1980) allows regional compacts to exclude waste from outside their regions and limited disposal options and because developing new disposal capacity will result in very costly disposal fees, biomedical researchers will continue to be motivated by economics and access to disposal to minimize sources and LLRW volumes. In addition, ever-increasing costs of waste treatment, storage, transportation, and disposal have had substantial impacts on volume reduction.

USE OF NONRADIOLOGICAL MATERIALS

Substituting nonradioactive materials for radioactive ones or shorter-lived materials for longer-lived ones is becoming more common. For example, biomedical researchers are substituting ^{33}P for ^{32}P and ^{35}S because of the shorter half-life and the potential for lower personnel exposure. Other substitutions involve the use of colorimetric, chemiluminescent, and bioluminescent assays for radioactive assays. And researchers are using an enzymatically catalyzed amplification process called polymerase chain reaction (PCR) to produce high-concentration gene sequences that can be detected by nonradioactive methods, such as the use of fluorescent dyes. Sensitivity, cost, and chemical hazards of the alternative need to be measured against the cost and availability of disposal of radioactive materials when substitutions are considered. Ideally, substitutes should provide equivalent or superior sensitivity, and accuracy, while not posing a greater threat to public health and safety than the radioactive material. The nonradioactive material should not make the research more expensive or labor intensive, and the cost of switching to a new methodology needs to be considered. For example, if experimental results in laboratories that have been based on use of a radioactive label are to be used as a standard, switching to a nonradioactive methodology will usually require recalibration or confirmation of the initial results and this can often be a significant financial cost to the biomedical research. Substitution of less hazardous chemicals is also used in the case of biomedical research that results in the generation of mixed waste.

Radioactive substances have several characteristics that make them attractive for laboratory investigations. They can be covalently bound to proteins, such as immunoglobulins, and provide an easily quantified product that maintains antibody activity and specificity. Radionuclides bound to ligands of various types can be used to provide an *in vivo* image or to deliver radioactivity to specific anatomic sites, such as a deposit of cancer cells, for therapeutic purposes.

Those characteristics are functional and useful features of radioactive materials, but there are attractive nonradioactive alternatives. The increased use of radionuclides coincides with the introduction of the radioimmunoassay (RIA). This technology allowed for the rapid and accurate measurement of small amounts of materials, such as hormones, microbial products, and antigens (Miller, 2000). RIA was often performed by radiolabeling an antibody protein with ^{125}I or ^{131}I, short-half-life radionuclides readily managed in waste with storage for decay. Several years after the introduction of RIA, new variations on antibody-based quantification were introduced. A good example is the enzyme-linked immunoassay (EIA), in which the label on the antibody molecule is an enzyme, such as horseradish peroxidase, rather than a radionuclide. The assay is based on colorimetric measurement of enzymatic activity with an enzyme substrate that undergoes a color change. EIA is an attractive alternative for assays because each enzyme molecule attached to an antibody provides an amplification mechanism for detecting bound antibody. EIA replaced RIA in most uses because it is a superior technology and it avoids the costs and bother of managing radioactive materials and radioactive wastes.

A similar set of alternatives has been developed with regard to nucleic acid sequencing. DNA base sequencing was developed by using gel separations of DNA fragments internally labeled with ^{32}P or ^{33}P. Although accurate, that method was not readily adaptable to the large-scale sequencing needed to sequence the genome of an entire organism. Robots were invented that could use colorimetric assays, and these assays have facilitated the determination of the base sequence of the DNA of several microorganisms and now of most of the human genome. As in the case of EIA, the development of alternatives was based on technologic improvements rather than a need to avoid the use of radioactive materials, but the alternatives have the effect of diminishing the reliance on radioactive materials by biomedical researchers (The Scientist, 1999, 2000; Griffin and Griffin, 1993; Glazer and Mathies, 1997; Mansfield et al., 1995, Kricka, 1991; Sandhu et al., 1991, Party and Gershey, 1995).

In some cases, the alternatives are still experimental and have yet to displace radioactive materials as the materials of choice. For example, radiolabeled antibodies are used for imaging and therapy in malignant disease. Radionuclides can deliver a dose of ionizing radiation to tumor cells and are useful for diagnostic imaging. Radiomimetic drugs could be substituted for radioactive materials, and toxins, such as ricin toxin, have generated considerable interest. But those substances cannot be used for imaging. The therapeutic and diagnostic uses of monoclonal antibodies are still evolving, and radioactive materials are likely to be an important component of means to amplify the specificity of antibodies with an additional function, such as imaging or directed toxicity.

Most large research institutions make a concerted effort to find suitable and appropriate alternatives to radioactive materials for research. The National Institutes of Health (NIH), as an example of a very large research center, created a committee to explore and promote the use of alternatives. These efforts are often useful on urban campuses, where neighbors might have concerns about the local environment. Committees like the NIH Committee on Alternatives to Radioactivity can provide information to investigators who are not aware of appropriate alternatives.

5

CONCLUSIONS

This report assesses the impact of lack of access to LLRW disposal facilities and the rising costs of LLRW disposed on biomedical research. We expect most of our observations to apply to medical uses of radioactive materials in diagnosis and therapy, but we focused our attention on waste generated in biomedical research and radioactive material suppliers to the biomedical research facilities. Hospitals and academic institutions have been storing radioactive materials onsite for decay for many years because it has been the least expensive and easiest method to deal with short-half-life radionuclides. Despite the extensive use of storage for decay, small volumes of LLRW still need to be sent to disposal facilities. Although disposal capacity in US Nuclear Regulatory Commission licensed facilities nationwide appears to be sufficient for the biomedical needs of the next several decades, the future of commercial LLRW management in the United States is by no means stable beyond that time frame.

The committee has concluded that the central issue in biomedical research LLRW management is cost. Assuming that there might be access to disposal facilities, there is sufficient disposal capacity for the relatively small amount of radioactive waste that the biomedical enterprise produces, and current practices are safe and covered by appropriate regulations. Therefore, the committee chose, in its analysis and recommendations, to focus on cost. However, for some institutions, factors other than cost may become paramount. For example, a large research institution in an urban setting may find that allocating sufficient space for LLRW activities, or the effect that storing radioactive materials has on public relations with neighboring populations, are more pressing issues than costs. Conversely, a small research activity in an institution without an extensive supporting infrastructure may not be able to handle the mechanics of waste disposal, even if the costs are manageable. Whether it is the single most important issue or not, we believe that costs are an important issue at virtually all research institutions.

The biomedical research community has adapted to the challenges presented by national, LLRW compact and state policies for LLRW management. The challenges have been these:

- Increased costs of onsite or offsite storage, treatment, and disposal. The costs of biomedical LLRW management have risen sharply in the last decade. An important driver of the increase has been the large increase in the cost of shipping and disposing of LLRW at licensed sites. Those increases have caused investigators and institutions to turn to an increased use of storage for decay which requires institutions to devote space and staff support to expanded storage of LLRW. This is an appropriate but expensive approach.

- Temporary interruptions in disposal access. In several instances, access to disposal sites has been closed to investigators from some states. Such closures indicate stresses that would be created by any situation that interrupted access to disposal. Although no state has been denied access for more than six years, there is some indication that denial of access for a longer period of time (10-20 years) would have adverse effects on biomedical research or medical care. The adaptations chosen by institutions and investigators in those states are discussed in this report: increased use of nonradioactive alternatives, increased use of storage for decay, and better management of radioactive-material techniques, such as ordering only the amounts of radionuclides needed. Costs increased, as did the uncertainty about the effects on clinical programs. Fortunately, the interruptions were terminated before any discernible major damage to biomedical research or medical care.
- A complex and potentially conflicting regulatory setting in which to manage LLRW. Radioactive materials are largely regulated by the US Nuclear Regulatory Commission, but they occasionally are to be disposed of in conjunction with solvents or other materials that are regulated as hazardous materials by EPA. States and local governments also have applicable regulations. The situation is often confusing and difficult for institutions and investigators.
- Uncertainty regarding the future of LLRW-disposal access and continuity of regulation that drives LLRW-management strategies. The fact that access to disposal has been interrupted in some states and the fact that creating new disposal sites has forced those who must manage LLRW to look for strategies that will work effectively even if access to disposal is denied.

Those challenges have caused generators to seek alternative storage, treatment and disposal strategies, as follows:

- Expansion of onsite management (storage for decay) for most commonly used radionuclides with short half-lives. Storage for decay has always been part of LLRW management, but the amounts and types of radionuclides being stored has grown as disposal has become more expensive. This growth requires a substantial increase in space devoted to storage and in staff effort and recordkeeping. For large urban campuses, finding the available space can pose a serious problem.
- Direct disposal or incineration of ^{14}C and ^{3}H, the most commonly used longerlived radionuclides. This is an environmentally appropriate strategy for these radionclides because the amounts being disposed of are very small, especially in comparison with the substantial amounts of naturally occurring ^{14}C and ^{3}H.

- Development and evaluation of alternative nonradioactive test procedures. Many alternatives that use chemiluminescence or enzyme quantitation have arisen recently and are superior for particular research tasks. That these alternatives use nonradioactive materials is itself a benefit.
- Improvement of management practices. The improvements include reduction in quantities of radioactive materials ordered, reduction in wastes generated during use, sorting and segregation of noncontaminated items, and overall minimization of final waste quantities and volumes.
- Expansion of the commitment of space, personnel, and infrastructure to onsite management of LLRW.

Overall, those adaptations have been safe, appropriate, and functional, albeit expensive.

The selection and use of radioactive material in biomedical research seems to depend most on the efficacy of such materials for their intended purpose. Although it is affected by access to disposal and by government policies related to LLRW management, its use is not strongly dependent on them. That will probably remain true in the future.

Biomedical use of radionuclides has declined, as nonradioactive alternatives have become increasingly popular as costs for LLRW management have increased sharply. However, some continued use seems likely, so the disposal problem will still be exist.

The current system of biomedical-LLRW disposal creates several burdens. One burden is on the regulators, who must oversee a widely distributed system that operates in many settings. Another is on research institutions, which have to fund and maintain expanded systems for storage and disposal; funding for this institutional effort must compete with other costs of doing research that are usually recovered as indirect cost funds.

It is extremely unlikely that new disposal sites will be developed. There is no pressing need for new capacity. There is substantial public opposition to new-site development. The cost of new-site development is high—exceeding $100 million/site—as illustrated by the recent experience of trying to develop a disposal site in California, Illinois, North Carolina, or elsewhere (Ryan and Newcomb, 2000).

The greatest risk to the current status of LLRW management in the biomedical research community is an unscheduled and arbitrary closing of current disposal facilities. To maintain existing facilities requires sustained political will and user support.

Understanding of the economic basis of LLRW-disposal policy and management strategies needs to be improved. In the main, financial considerations determine which of the available options will be chosen.

If use of radionuclides increases because of the larger national commitment to biomedical research or because of the introduction of new radioassay or radiotherapeutic systems, or if the use of longer-half-life radionuclides increases for any reason, the available system of LLRW management storage, monitoring, inspection, and disposal might not be adequate to meet the needs of this expansion.

Although disposal capacity appears to be sufficient for the biomedical research community needs of the next several decades, the future of biomedical-research LLRW management in the United States is not ensured for the longer term. Interruption in access whether from existing site closure, impacts on transportation, or real or perceived problems with alternative storage methods may create more immediate needs for alternative storage or disposal facility development. Although the biomedical research community has adapted to changes in LLRW policy and management options, further stress might not be as well tolerated.

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RECOMMENDATIONS

The current situation results in a series of substantial costs to institutions, such costs as those for securing and preparing space for storage-for-decay, maintenance, training, and recordkeeping and the cost entailed in the removal of space from other productive uses. Therefore, biomedical research institutions must provide adequate funds for facility management. It is important to understand that the process of LLRW disposal management policy must make financial sense. Therefore, the committee recommends that institutions engaged in biomedical research carefully assess their LLRW management practices for cost effectiveness. Furthermore, the committee recommends that funding agencies modify their support mechanism for infrastructure costs to pay their fair share of the cost of LLRW management and disposal. Agencies engaged in the support of biomedical research need to take into consideration that the costs of radioactive-waste management, a necessary component of research, have risen sharply in recent years.

The committee is concerned about the ability of the current LLRW management system to adapt to major increases in use of radioactive materials. If use of radioactive materials increases because of the larger national commitment to biomedical research or because of the introduction of new diagnosis and treatment methods, or if the use of longer-half-life radioactive materials increases for any reason, the current system will need to change. Policy makers have been sensitive to the special needs of medical research, as illustrated by the policy exemptions for ^{3}H and ^{14}C. The new challenge of rapidly rising costs will pose a different kind of policy problem. Regulatory and legislative bodies will need to understand the changing economic basis of LLRW disposal policy so that they can modify the system in the event of major new needs. A more thorough analysis of the economics of LLRW management and disposal is recommended.

Institutional efforts to promote the use of appropriate alternatives to radioactive materials for research are useful and should be commended and strongly encouraged. The committee recommends that such agencies as NIH be encouraged to hold conferences or symposia to share information on effective alternatives to radioactive materials for biomedical research.

The regulatory environment for the biomedical research community is complex; any efforts that the regulatory community could make to simplify or streamline the regulatory requirements for managing LLRW without compromising worker or public health and safety would be a benefit.

APPENDIX A

Cost Trade off Analysis

A decision to dispose of waste directly or to process it before disposal is principally an economic decision. For the biomedical-waste generator, decisions to proceed with treatment and disposition, including disposal and recycling can be governed by simple relationships. The decision to dispose directly is governed by:

$$\mathrm{DDC}\ (V_1) < f_m\ \{\mathrm{WTC}\ (V_1) + \mathrm{TDC}\ (V_2) - \mathrm{TTC}\ (V_1 - V_2)\} + \mathrm{OMC}$$

Where:

DDC = direct radioactive material disposal costs for initial volume, V_1
WTC = treatment costs to treat V_1
TDC = disposal costs for reduced volume, V_2
TTC ($V_1 - V_2$) = reduction in transportation costs by shipping the smaller volume
f_m = modifying factors that weight treatment options for institutional goals, policies or requirements. For an analysis based strictly on financial drivers, $f_m = 1$. If an institution has limited storage space and offsite disposal is restricted, then $f_m < 1$. If onsite storage is not restricted or if access to disposal capacity is not an issue then $f_m > 1$
OMC = other institutional LLRW management costs
V_1 = is the untreated volume
V_2 = is the treated (reduced) volume

This equation, no matter how complex the treatment option, allows for evaluation of direct disposal of LLRW versus treatment.

In reality the situation is more complex. Treatment may result in disposal of a reduced volume of radioactive material, recycle of some non-radioactive material, disposal of some non-radioactive materials

$$\mathrm{DDC}\ (V_1) < f_m\ \{\mathrm{WTC}\ (V_1) + \mathrm{TDC}\ (V_2) + \mathrm{TTC}_r\ (V_1 - V_2) + \mathrm{ODC}\ (V_3) + \mathrm{TTC}_{nr}\ (V_3) + \mathrm{OMC} - \mathrm{RMV}\ (V_4)\}$$

Where:

DDC = direct radioactive material disposal costs for initial volume, V_1
WTC = treatment costs to treat V_1
TDC = disposal costs for reduced volume, V_2
ODC = disposal cost for waste disposed as non-radioactive waste (V_3)
TTC_r = reduction in transportation costs by shipping the smaller volume
TTC_{nr} = transportation costs for non-radioactive waste shipping
f_m = modifying factors that weight treatment options for institutional goals, policies or requirements. For an analysis based strictly on financial drivers, $f_m = 1$. If an institution has limited storage space and offsite disposal is restricted, then $f_m < 1$. If onsite storage is not restricted or if access to disposal capacity is not an issue then $f_m > 1$

OMC = other institutional LLRW management costs
RMV = recycle metal value V_4
V_1 = is the untreated volume
V_2 = is the treated (reduced) volume
V_3 = is the non radioactive disposed volume
V_4 = is the recycled volume

The relationship among the options of:

Direct disposal;

Evaluation and release for recycle with direct disposal of ONLY those materials not meeting the criteria without treatment;

Evaluation and release for recycle with direct disposal of ONLY those materials not meeting the criteria with aggressive treatment to minimize what is disposed as radioactive material; and

Costs for treatments, transportation, direct disposal, measurement and assessment of materials, and management should be carefully assessed and included in the analyses.

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GLOSSARY

Alpha particles:	positively charged particles emitted from some radionuclides during radioactive decay. An alpha particle contains the same components as a nucleus of a helium atom (two protons and two neutrons). They travel very short distances in air. Alpha-emitting radionuclides are of most concern to humans if ingested or inhaled.
Atom:	the smallest part of an element that still has all properties of that element. Its nucleus consists of protons and neutrons and is surrounded by orbiting electrons.
Background radiation:	the amount of radiation to which a member of the population is exposed from natural sources, such as naturally occurring radionuclides in the soil, cosmic radiation occurring in outer space, and naturally occurring radionuclides deposited in the human body.
Beta particles:	negatively charged particles emitted from the nucleus of an atom and having a mass and charge equal to that of an electron. Fast moving, energetic, beta particles can penetrate the skin. Beta emitting radionuclides are both an internal and an external hazard.
Curie (Ci):	a quantity of radioactive material in which 3.7 x 10^{10} atoms are disintegrating per second (3.7 x 10^{10} Bq).
Class A waste:	includes radionuclides with the lowest concentrations and short half-lives and constitutes 95% of all low-level waste.
Class B waste:	allows intermediate concentrations of both long-lived and short-lived radionuclide materials. Class B wastes must also meet certain stability requirements.
Class C waste:	allows the highest concentrations of both long-lived and short-lived radionuclide materials. Class C wastes must be disposed of in conformance with intrusion-barrier and depth requirements.
Compact:	a group of two or more states formed to manage low-level radioactive waste on a regional basis. Forty-two states have formed nine compacts.
Decommissioning:	the process of closing down a facility followed by reducing residual radioactivity to a level that permits the release of the property for unrestricted use criteria (10 CFR 20.1003).
Element:	an atom with a unique number of protons in its nucleus. For example, oxygen has eight protons in its nucleus, and plutonium has 94.

Gamma ray:	a penetrating, short-wavelength electromagnetic radiation emitted during the radioactive decay of many radioactive materials. Except for their origin (the nucleus of the atom, rather than the outer electron shells) and higher energy, their characteristics are similar to those of x-rays. Gamma radiation is the most penetrating of the common kinds of ionizing radiation and is of concern as an external and internal radiation hazard.
Half-life:	the time in which half a collection of atoms of a particular radioactive substance disintegrate into atoms of another element. Half-lives range from millionths of a second to billions of years.
High-level radioactive waste (HLW):	(1) Irradiated (spent) reactor fuel. (2) Liquid waste resulting from the operation of the first-cycle solvent-extraction system, and the concentrated wastes from later extraction cycles, in a facility for reprocessing irradiated reactor fuel. (3) Solids into which such liquid wastes have been converted. HLW is primarily in the form of spent fuel discharged from commercial nuclear power reactors. It also includes some reprocessed material from defense activities and a small quantity of reprocessed commercial HLW (10 CFR Part 60) (USNRC, 1999b).
Isotopes:	nuclides that have the same number of protons in their nuclei, and hence the same atomic number, but that differ in the numbers of neutrons, and therefore in the mass number; chemical properties of isotopes of a particular element are almost identical.
Low-level waste (LLW):	includes wastes that are not high-level wastes (HLW), transuranic waste (TRU), naturally occurring radioactive materials (NORM), or source-material waste defined under the Atomic Energy Act Section 11.(e) (2). LLRW includes waste that come principally from nuclear power generation; hospitals and medical, educational, and research institutions; industries; private or government laboratories; and other nuclear fuel-cycle facilities (such as, fuel fabrication plants).
Mixed low-level radioactive and hazardous waste (mixed LLW):	is defined as waste that satisfies the definition of low-level radioactive waste (LLRW) in the Low-Level Radioactive Waste Policy Amendments Act of 1985 (LLRWPAA) and contains hazardous waste that either (1) is listed as a hazardous waste in Subpart D of 40 CFR Part 261 or (2) causes the LLRW to exhibit any of the hazardous-waste characteristics identified in Subpart C of 40 CFR Part 261.
Positron emission tomography (PET):	a non-invasive, diagnostic imaging technique for measuring the metabolic activity of cells in the human body. It is useful clinically in patients with conditions affecting the brain and the heart and in patients with particular types of cancer.

Radioactivity:	a property of radioactive material whereby atoms undergo spontaneous transformation at a predictable and measurable rate. Units of activity are the becquerel (Bq) and curie (Ci); 1 Ci = 3.7 x 10^{10} disintegrations per second, and 1 Bq = 1 disintegration per second.
Radioimmunoassay:	quantitative determination of antigen and antibody concentrations by the introduction of a radioactively labeled, complimentary substance that can be expected to bind to the molecules in question and the measurement of a resulting radioactive immune complex.
Radioactive contamination:	radioactive material that is present in an unwanted location and has no useful purpose.
Radionuclide:	a radioactive species of an atom characterized by the constitution of its nucleus.
Sealed source:	any special nuclear material or byproduct encased in a capsule designed to prevent leakage or escape.
Waste, radioactive:	solid, liquid, and gaseous materials derived from licensed radioactive material operations that contain radioactive material in licensed amounts for which there is no further useful purpose. Wastes are classified as high-level waste (HLW) as defined in 10 CFR 60 or as low-level radioactive waste (LLRW) as defined in 10 CFR 61.
Waste, transuranic:	material contaminated with transuranic elements that is produced primarily from reprocessing spent fuel and from use of plutonium in fabrication of nuclear weapons.
X rays:	electromagnetic waves or photons not emitted from the nucleus, but normally emitted by energy changes in electrons. Energy changes occur in electron orbital shells that surround an atom or in the process of slowing down, in an x-ray machine.

COMMITTEE BIOGRAPHIES

Sidney H. Golub, Ph.D., (Chairman), is Executive Director of FASEB (The Federation of American Societies of Experimental Biology). He was formerly a Professor of Microbiology and Molecular Genetics at the University of California, Irvine, where he also served as the chief academic officer, and the Executive Vice-Chancellor. His research interests include regulation of cytotoxic cell functions and the immunology of human malignant disease. A recent area of interest is the study of ethical issues in medicine and research. Throughout his career, Dr. Golub has served on many committees and review panels such as the NCI breast cancer task force, chair of the University of California Cancer Research Coordinating Committee, and chair of the Veterans Administration Oncology Merit Review Board. Dr. Golub has published over a hundred journal articles and eighteen book chapters.

Carol Campbell Amick, is an Environmental Consultant in Bedford, MA. She received a Master in Public Administration from Harvard University in 1981, and is a former Executive Director, Commonwealth of Massachusetts Low-Level Radioactive Waste Management Board, Boston, MA. Ms. Amick developed and implemented all LLRW management policies and represented Massachusetts Governors Dukakis, Weld, and Cellucci at national LLRW meetings. She authored the Massachusetts LLRW management plan, acclaimed by state government policy makers and national LLRW publications. As a State Senator for Massachusetts, she chaired the Legislature's Committee on Natural Resources and Agriculture and authored key environmental laws including the Solid Waste Management Act, State “Superfund” Law, Low-Level Radioactive Waste Management Act, and Hazardous Waste Management Act. She was appointed by President Carter to the White House Water Policy Task Force and was named by the Environmental Lobby of Massachusetts “Legislator of the Year” for 1985, and recognized by the Massachusetts Association of Conservation Commissions for “unwavering dedication” to the environment.

Gloria Anderson, has been an active member of the League of Women Voters since 1965. She received her Master's degree in Speech from the University of Wisconsin in 1961. She was natural resources director on the board of the League of Women Voters of California for four years. She currently serves on the board of directors of LWV San Bernardino as well as the Water Education Foundation and is a volunteer in several other community organizations. Ms. Anderson was involved in the League's effort to facilitate public participation during the site selection process for the Southwestern Compact's LLRW disposal facility. She authored reports on the work of the LLRW site selection citizens advisory committee in 1987 and 1988 as well as a guidebook for citizen participation in 1990, with updates in 1994 and 1998. She served on the National Research Council's committee to Review New York State's Siting and Methodology Selection for Low-Level Radioactive Waste Disposal. Ms. Anderson represented the League on a committee of the California Environmental Protection Agency's Comparative Risk project. She has also served on various school district and local government advisory committees.

Michael T. Ryan, Ph.D., C.H.P., Associate Chair and Associate Professor, Department of Health Administration and Policy at the Medical University of South Carolina. Dr. Ryan received a Ph.D. in Health Physics in 1982 from the Georgia Institute of Technology, where he was recently inducted into the Academy of Distinguished Alumni. In 1989, he received the Health Physics Society's Elda E. Anderson Award. Dr. Ryan has held numerous offices in the Health Physics Society, including President of the Environmental Section. Over the past ten years, Dr. Ryan has served on the Technical Advisory Radiation Control Council for the State of South Carolina. He currently serves as Chair of the Council. He is a member of the National Council on Radiation Protection and Measurements (NCRP). He serves on their Board of Directors and is the chairman of scientific committee 87 and scientific Vice President for Radioactive and Mixed Waste Management. He holds adjunct appointments at Georgia Tech and at the University of South Carolina, where he has taught radiation protection courses on the graduate level. In addition, Dr. Ryan has authored many articles and publications in the areas of environmental radiation assessment, radiation dosimetry, and regulatory compliance for radioactive materials. Dr. Ryan's research, grants, and contracts are in the areas of regulatory compliance, compliance data management, occupational radiation dosimetry, environmental management, and radiation protection policy. Prior to his appointment at MUSC, Dr. Ryan was most recently the Vice President of Barnwell Operations for Chem-Nuclear Systems, Inc., and had overall responsibility for operation of the low-level radioactive waste disposal and service facilities in Barnwell, South Carolina. Dr. Ryan's area of responsibility included the implementation of the scientific programs that assure the safe and compliant operation of the company's low-level radioactive waste processing and disposal facilities.

Detlof von Winterfeldt, Ph.D., is a Professor of Public Policy and Management at the University of Southern California and Director of its Institute for Civic Enterprise. He also is the President of Decision Insights, Inc., a management consulting firm specializing in decision and risk analysis. His research interests are in the foundation and practice of decision and risk analysis as applied to technology and environmental management problems. He is the co-author of two books and author or co-author of over one hundred articles and reports on these topics. He has served on several committees and panels of the National Science Foundation (NSF) and the National Research Council (NRC), including the NSF's Advisory Panel for its Decision and Risk Management Science Program and the NRC's Committee on Risk Perception and Risk Communication.

STUDY DIRECTOR BIOGRAPHY

Isaf Al-Nabulsi, Ph.D., assumed the role of study director for the LLRW study in the Board on Radiation Effects Research (BRER). In addition, she directed the studies that produced the report *A Review of the Draft Report of the NCI-CDC Working Group to Revise the 1985 Radioepidemiological Tables, and a Letter Report to CDC: Review of the*

Savannah River Source-Term Report. Dr. Al-Nabulsi received her MS in radiation biology from Georgetown University and her Ph.D. in biomedicinal chemistry from the University of Maryland at Baltimore. She previously held a research associate position at Wake Forest University Baptist Medical Center. Her research interests include molecular mechanisms of DNA damage and repair, cytogenetic techniques, molecular mechanisms of tumor radioresponsiveness, the influence of hypoxic cells on the outcome of chemotherapy and radiotherapy, and the biological function of sigma receptors as potential biomarkers of tumor-cell proliferation. She is a member of the Radiation Research Society, the American Association for Cancer Research, the Health Physics Society, and Women in Cancer Research.